SNOW CHARACTERISTICS WITH THE BLADE HARDNESS GAUGE

by

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Abstract

Snow profiles are carried out in the snowpack to provide avalanche forecasters and technicians information of the snow stratigraphy relative to avalanche formation and propagation. Snow hardness, which is a measure of the snow's resistance to penetration by an object is a standard characteristic measured in a snow profile. The current International and Canadian standard technique for measuring snow hardness is the hand hardness test, which is a subjective test that can be compromised by human biases. The blade hardness gauge is a technology designed to quantitatively measure the hardness of snow in newtons of force.

During the 2020-21 and 2021-22 winter seasons, research was carried out in the mountains of British Columbia and Alberta to test the reliability and integrity of the blade hardness gauge in relation to measuring snow hardness. The research set out to determine standard techniques to use the gauge with respect to insertion rate of the gauge, the replication of the gauge and the orientation of the gauge to the snowpack. Blade hardness measurements were compared to snow density measurements, hand hardness measurements and extended column test results.

The blade hardness gauge proves to be a reliable and consistent tool for measuring snow hardness. The gauge should be inserted into the snow with an insertion rate of approximately 10 cm/s and oriented parallel to the snowpack to gain consistency amongst users. The gauge is more consistent amongst users for measuring snow hardness compared to the use of the hand hardness test. A chart was made to convert blade hardness to hand hardness to utilize the gauge as a teaching tool for the hand hardness test. The blade hardness measurements can be utilized to estimate snow density using linear and non-linear regressions. With the consistency and reliability of the blade hardness gauge it has potential for use as a teaching tool for the hand hardness test and for measuring snow hardness over time.

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BHG	Blade hardness gauge
N	Newtons of force
n	Sample size
CT	Compression test
ECT	Extended column test
R	Ram hardness
ρ	Snow density
H	Snow hardness
h	Hand hardness index
E	Snow grain size
~	Non-applicable data entry
$\approx$	Approximately equal to

Chapter 1. Introduction

Each winter season as the snow begins to fall, recreationalists and professionals flock to the mountains of western Canada in search of the illustrious feeling of riding powder. Unfortunately, the return of snow every year brings more than just joy to the public: between the years 2010-2020 there has been an average of 11 avalanche fatalities a year in Canada (Avalanche Canada, 2021). Avalanche activity also brings destruction to resources, damages infrastructure and causes disruptions to transportation corridors. It has been estimated that the economic loss due to avalanche activity, along transportation corridors in Canada, is over $125M a year (Sinickas et al., 2016).

Avalanche safety operations, including ski resorts, backcountry, industrial and highway, hire avalanche forecasters and technicians to mitigate the avalanche hazard. Avalanche mitigation serves the purpose of reducing or eliminating avalanche risk (Canadian Avalanche Association, 2016a). Types of mitigation can be short term (e.g. artificial triggering using explosives) or long term (e.g. static defenses including snow sheds and snow fences). Short term mitigation efforts require the work of avalanche forecasters.

The avalanche forecaster must interpret current weather and snowpack profiles to predict the outcome of future avalanche trends. Snow profile observations can be taken throughout the entirety of the snowpack to gain knowledge with respect to the snow depth, snow layers, snow hardness, grain form, grain size, liquid water content and snow density (Canadian Avalanche Association, 2016b). The current standard for measuring snow hardness in Canada outlined by the Canadian Avalanche Association is the hand hardness test. This MSc. thesis research focuses on methods and characteristics of measuring snow hardness.

With no standard method of quantitatively measuring snow hardness this research aims to test the reliability and integrity of the blade hardness gauge (BHG) in relation to measuring snow hardness. To test this the research was broken into separate components including insertion rate, gauge replication, orientation of the gauge and comparison between blade hardness measurements with hand hardness measurements, snow density measurements and extended column test results.

Chapter 1 of this thesis introduces important components of snow in relation to the study of snow and avalanches. A literature review is given of the ways of measuring snow hardness, snow hardness comparison with snow density and calibration of the hand hardness test. Chapter 2 describes the research methods utilized in this thesis to reach the components and goals of the research. Chapter 3 reports the results of the various measurements. Chapter 4 discusses techniques for using the BHG and discusses implications of the results such as a scale between the BHG and the hand hardness test. Chapter 5 provides conclusions of the study and lays out future research to be carried out with the BHG.

Snow

Snow crystals are formed in atmospheric clouds containing ice crystals and super cooled water droplets. The water droplets diffuse and crystalize onto the ice crystals until the crystals reach a critical size and begin to fall due to gravity (Canadian Avalanche Association, 2018). While the crystals fall, they can collide with other supercooled droplets and gain mass in a process known as riming (McClung & Schaerer, 2006). The snow crystal form depends on a multitude of factors with temperature and water vapour density being of high importance (McClung & Schaerer, 2006). Once the snow is on the ground it undergoes a continuous state of transformation known as metamorphism (Fierz et al., 2009). The variability of snow on the ground is compounded as the snow comprises of an aggregate of ice crystals, water vapour and water as the temperature stays close to the melting point of ice. Due to the combination of precipitation, wind transport, and the continuous state of metamorphism the snowpack is built up of distinct stratigraphic layers (Fierz et al., 2009). With the combination of snow metamorphism, weather patterns and terrain there is constant temporal and spatial variability within the snowpack.

Temperature gradients and pressure within the snowpack are the main factors behind snow metamorphism. The temperature at the ground level stays at approximately 0°C while the temperature at the snow surface can fluctuate based on the air temperatures, generally staying cold and ranging from -40°C to 0°C during the winter (Armstrong, 1981). The initial snow grains, called precipitation particles (PP), decompose into fragmented particles (DF) and then either become rounded grains (RG) or faceted grains (FC). If there is a large temperature gradient in the snowpack (10-20°C/m) the snow grains exhibit high crystal growth rates through the transfer of water vapour to become faceted grains. If there is a small temperature gradient in the snowpack (<10°C/m) the snow grains grow by vapor condensation into rounded grains (Colbeck, 1983). Faceting snow generally results in weak layers in the snowpack while rounding snow generally results in the strengthening of the snow layers (McClung & Schaerer, 2006). As the snowpack increases in thickness throughout the winter season the stratigraphic layers can gain or lose strength depending on the temperature, density, and permeability.

Snow metamorphism is also due to pressure in the snowpack. In a simple horizontal snowpack with a constant depth the snowpack exhibits deformation vertically due to gravitational forces resulting in a pressure gradient. The snowpack on a slope exhibits deformation comprised in the combination of three factors: (1) tension, snow grains are pulled apart; (2) compression, snow grains are forced together; and (3) shear, snow grains are forced past each other (McClung & Schaerer, 2006).

Weak layers in the snowpack are layers of snow that are less cohesive to the adjacent layers. They are further classified into non persistent weak layers, generally formed by large precipitation particles, and stabilize within a few days, and persistent weak layers, formed by faceted crystals, surface hoar or depth hoar and can persist in the snowpack for weeks or months (Jamieson, 1995).

Avalanches

Avalanches involve masses of snow rapidly descending slopes due to the force of gravity. The two main forms of avalanches are loose-snow avalanches (Figure 1.1) and slab avalanches (Figure 1.2). Loose-snow avalanches start at a single point on or near the surface consisting of low cohesive snow. Slab avalanches are associated with a weak layer buried under a slab of cohesive snow (Schweizer et al., 2003). Dry snow slab avalanches are generally more dangerous and the focus of the proposed research. There are three prominent components responsible for dry avalanches; the slab, which is the mass of snow that slides, the weak layer, a layer that is less cohesive to the adjacent layers, and the bed surface, the surface that the slab slides on. The thickness of a slab has a range of ten to hundreds of centimeters and the thin weak layer has a range of about one to hundreds of millimeters (McClung, 2021). Further features of a slab avalanche include the crown, the upslope boundary of the fracture line, the flanks, the two side boundaries of the fracture line and the stauchwall, the downslope boundary of the fracture line (Perla, 1975). An image illustrating the described features of a slab avalanche is seen in Figure 1.3.

Figure 1.1. Multiple loose-snow avalanches (photo by Steve Crowe).

Figure 1.2. Slab avalanche (photo by Steve Crowe).

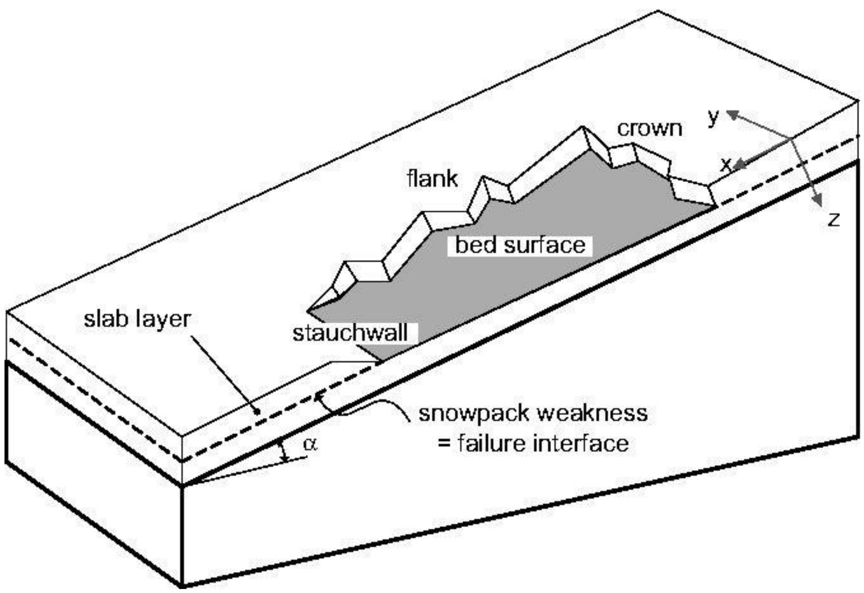

Figure 1.3. Schematic of slab avalanche illustrating the slab, weak layer/interface (dashed line), bed surface (grey area), crown, flank and stauchwall (Schweizer et al., 2003).

Avalanche Forecasting

Avalanche forecasting is used by all avalanche safety operations. Avalanche forecasters are hired to interpret the current weather patterns, weather forecasts, snowpack, and avalanche observations to predict avalanches and communicate hazards associated within the avalanche terrain. The forecasters must consider a multitude of factors for managing terrain that they oversee. These factors have been grouped together into three classes and as the class number increases so does the amount of uncertainty (McClung & Schaerer, 2006). These groups of factors are seen in Table 1.1. Class I factors are mostly non-numerical and provide direct evidence of the avalanche conditions. Class II factors offer a rule-based approach such as looking at the individual layers (snow stratigraphy) of the given snowpack. Class III factors are mostly numerical such as the amount of precipitation or wind speed. The proposed research will be focusing on factors associated with Class I and Class II including instability tests and snow hardness.

Table 1.1. Classes of avalanche forecasting factors (McClung & Schaerer, 2006).

Class	Examples
I: Instability Factors	Avalanche occurrences, instability test, cracking underfoot
II: Snowpack Factors	Snow stratigraphy, snow temperatures, snow hardness, snow density, grain types/size
III: Meteorological Factors	Precipitation, wind, temperature, radiation by sun, weather forecast

Snow Profiles

A snow profile is a systematic method of recording the observed stratigraphy and characteristics of individual layers in the snowpack. Snow profiles are carried out by digging a vertical cross-section of the snowpack as seen in Figure 1.4. The location of a snow profile varies across topographical locations depending on the goals of the avalanche technician.

Across the globe observation guidelines and recording standards have been set for snow profiles such as “The International Classification for Seasonal Snow on the Ground” (Fierz et al., 2009). The snow profiles carried out in this study follow the “Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches” set by the Canadian Avalanche Association (Canadian Avalanche Association, 2016b).

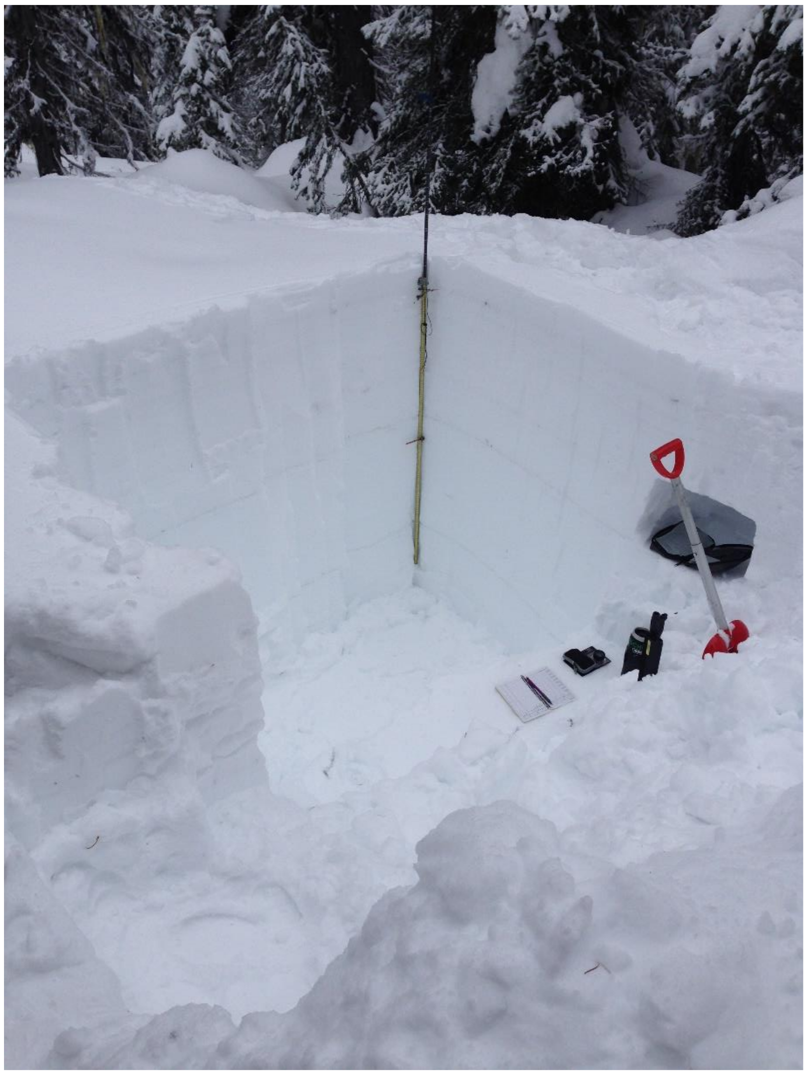

Figure 1.4. Snow profile carried out in dry alpine snow located in the Okanagan Highlands (photo by author).

Snow Instability Tests

Snow instability tests are used by professional avalanche technicians and recreationalists to identify weak layers within the snowpack and test the slope's stability. One of the most common instability tests is the Compression Test (CT) developed by Parks Canada wardens in the mid 1970s (Jamieson, 1999). The CT consists of isolating a column of snow that is 30 cm x 30 cm with a max depth of 120 cm and is loaded by tapping on a shovel blade placed at the top of the column. Comparing skier triggered avalanches with CTs showed that as the number of taps increased the probability of skier triggered avalanches decreased (Jamieson, 1999). A schematic of the CT can be seen in Figure 1.5 illustrating the isolated 30 cm x 30 cm snow column and utilizing a shovel blade on top of the column.

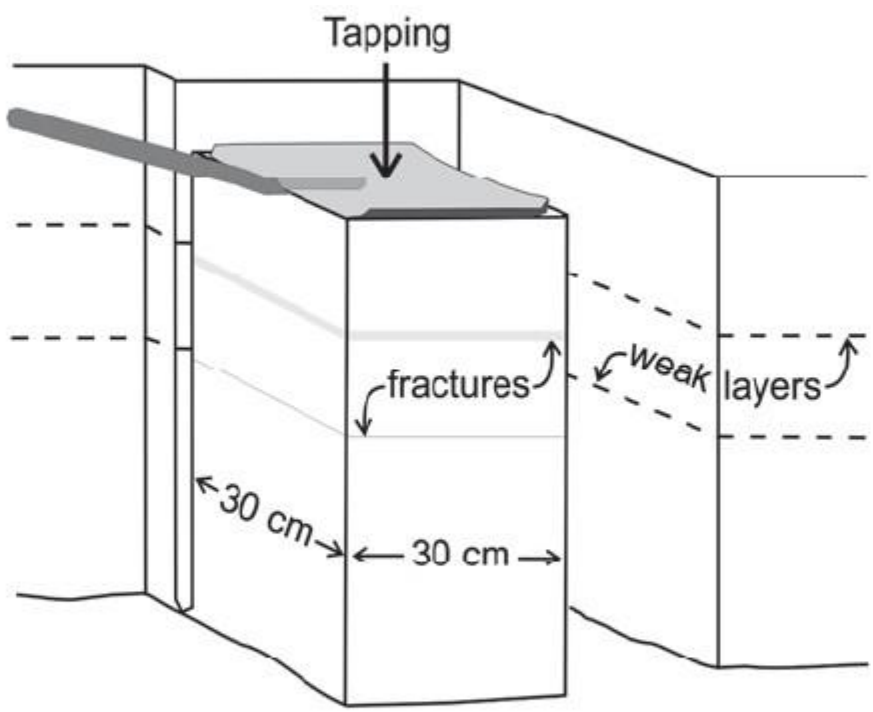

Figure 1.5. Schematic of a compression test with an isolated 30 cm x 30 cm column of snow (Canadian Avalanche Association, 2016b).

The CT is used to test the snowpack in relation to fracture initiation (Simenhois & Birkeland, 2006). The Extended Column Test (ECT) is designed to test the snowpack for both fracture initiation and propagation. This is done by extending the isolated column of snow to be 30 cm (downslope) x 90 cm (across slope) (Simenhois & Birkeland, 2006). Further studies have shown the ECT has a lower false-stability rate then other instability tests like the CT (Ross & Jamieson, 2008; Simenhois & Birkeland, 2009). The ECT is explored in comparison with the BHG in this research. A schematic of the ECT can be seen in Figure 1.6 illustrating the 30 cm x 90 cm isolated column of snow and placement of the shovel blade.

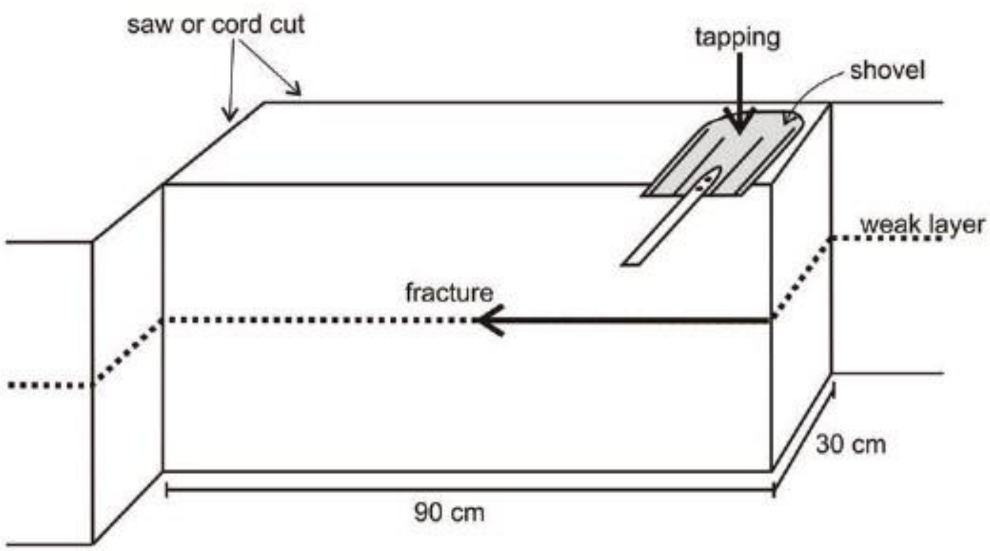

Figure 1.6. Schematic of an extended column test with an isolated 30 cm x 90 cm column of snow (Canadian Avalanche Association, 2016b).

Snow Hardness History

A predictive tool 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 snow's 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).

Snow hardness has been described from as early as 1885 by Heim, a pioneer of glaciology, who described the changes in the hardness from new snow to glacier ice. In 1930, Welzenbach differentiated two categories for hardness, packed snow and pressed snow. A snow profile technique designed by Paulcke, in 1938, resulted in the first iteration of the hand hardness test.

This technique involved describing the ease of penetration of a finger into different stratigraphic snow layers (Pielmeier & Schneebeli, 2003a).

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 snow resistograph was invented utilizing a probe with a horizontal blade on the end, when the probe gets to the bottom of the snowpack it is turned 90 degrees and withdrawn upwards with the resistance of the snow on the thin part of the blade being recorded (Bradley, 1966). An advantage of the resistograph was that it outputted a graphical hardness profile but had a high cost and high mass (Pielmeier & Schneebeli, 2003a). The snow resistograph showed that varying the rate of withdrawing the blades through the snow varied the resistance measurements with a rate of 10 cm/s being the optimum withdrawing rate for consistency (Bradley, 1966). Further work was done making a digital snow resistograph (Brown & Birkeland, 1990; Dowd & Brown, 1986) but it was ultimately unable to detect thin weak layers and lacked durability (Schneebeli & Johnson, 1998). The electric cone penetrometer (Schaap & Föhn, 1987) tried filling this void of reliably measuring snow hardness but also was unable to detect thin weak layers (Schneebeli & Johnson, 1998). The SnowMicroPen (SMP) is a motor controlled, high spatial resolution penetrometer (Schneebeli & Johnson, 1998) utilizing a 5 mm cone diameter, compared to the Swiss rammsondee's 40 mm cone diameter. With the high resolution and smaller cone diameter the SMP can accurately detect the presence of weak layers (Johnson & Schneebeli, 1999; Pielmeier & Schneebeli, 2003b; Schneebeli & Johnson, 1998). Although the SMP can detect weak layers in the snowpack it is not commonly used amongst avalanche practitioners due to its size, weight, and high costs (Lutz & Marshall, 2014).

In 2012 a group of MIT graduates started the company AvaTech to produce a rapid snow penetrometer (Christian et al., 2014). During the winter of 2013-14 the AvaTech SP1 was tested by the manufacturers and independent researchers. The SP1 was designed to record hardness profiles and additional information such as depth of snowpack. Lutz and Marshall (2014) reported the SP1 recorded consistent hardness values, but needed improvements with respect to snowpack depth, data from the upper snowpack and detecting the presence of buried weak layers. In 2016, AvaTech released the SP2 as an improvement to the SP1 (Pielmeier & van Herwijnen, 2016). Between January and March 2016, Pielmeier and van Herwijnen carried out side by side hardness profiles with the SP2, SMP and Swiss rammsonde. It was found that the SMP was still superior to the SP2 for accurate positioning of hardness measurements with respect to snowpack depth and the presence of buried weak layers (Pielmeier & van Herwijnen, 2016). To date AvaTech is no longer in operation but has been replaced by Propagation Labs. Propagation Labs currently is making “The Snow Scope Probe” but at the time of writing has no published papers or proceedings researching the validation of the probe.

The current standard for measuring snow hardness in Canada is the hand hardness test, introduced by De Quervain in 1950 (Canadian Avalanche Association, 2016b). 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, 2016b). 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).

Fukue (1977) utilized a thin blade penetration technique for measuring snow characteristics with four goals in mind: (1) involved a simple technique, (2) minimized effect of speed/penetration rate, (3) minimized densification of snow during testing, and (4) minimized the change of snow grain bonding during testing. Fukue mounted the thin blade, 12 mm wide and 0.6 mm thick, onto an actuator that mechanically inserted the blade into the snow. The testing found a ductile to brittle transition at a penetration rate of 0.25 mm/s with the snow exhibiting ductile properties below 0.25 mm/s and the brittle properties above 0.25 mm/s. In the snow exhibiting brittle properties it can be assumed that the thin blade penetration was measuring snow characteristics without the change of the initial properties such as density (Fukue, 1977).

In 2011 Borstad and McClung introduced the blade hardness gauge (BHG) to measure snow hardness in a quantitative manner (Borstad & McClung, 2011). The BHG utilizes a thin blade (0.6 mm thick), which is the average sized snow grain of alpine snow and is used to minimize snow compaction. The first iteration of the BHG is seen in Figure 1.7. The first iteration had an operating temperature range of -1 to 49 °C and a load cell capacity of 250 N with a resolution of 0.1 N (Borstad & McClung, 2011).

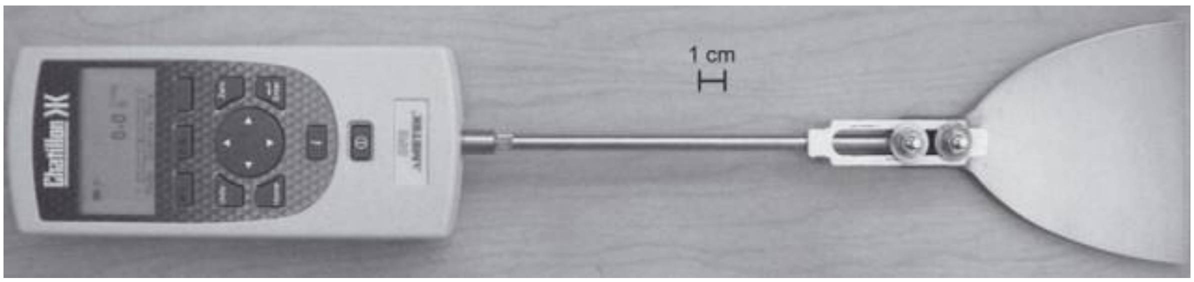

Figure 1.7. First iteration of the BHG designed by Chris Borstad and David McClung (Borstad & McClung, 2011).

In 2013, Buhler custom built a BHG, as seen in Figure 1.8, to measure the hardness of snow crust layers. It utilized the same size blade as the first iteration designed by Borstad and McClung. The BHG was able to track the hardness of the snow crust layers over time and found a correlation between hardness and snow density (Buhler, 2013).

Figure 1.8. Custom BHG created by Buhler to measure snow hardness (Buhler, 2013).

Further iterations of the BHG were produced by Fraser Pogue. In 2016 his first iteration of the BHG, seen in Figure 1.9, utilized 3D printing to build the enclosure to attach the thin blade (0.6mm thick, 10 cm wide) to the components of the force sensor. This enclosure was made to be small, lightweight, and waterproof. The force sensor had a range of 0.05-49 N, was accurate to 0.1% and an operating temperature range of -20 to 40 °C. The thin blade allows the avalanche practitioner to measure the hardness of thin weak layers over time (Pogue & McClung, 2016). During the winter of 2016-17 Parks Canada staff in Glacier National Park used the BHG in 27 snow profiles by 8 different operators. The BHG used in this study was Pogue's second iteration of the gauge, seen in Figure 1.10. This iteration of the BHG was designed to be friendlier for operational use. The Parks Canada study 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). The research in this thesis continued working with the BHG to determine its reliability and integrity in relation to measuring snow hardness.

Figure 1.9. Blade Hardness Gauge produced by Fraser Pogue in 2016 (Pogue & McClung, 2016).

Figure 1.10. Blade Hardness Gauge produced by Fraser Pogue in 2017 (Pogue et al., 2018).

Snow Hardness Comparison with Snow Density

Density is a measurement of mass per unit volume. To obtain the density of snow, one measures the mass of a sample of snow of known volume. For samples of dry snow, the sample is a mixture of ice and air. For samples of wet snow, the sample is a mixture of ice, liquid water, and air. Snow increases in density due to the rearrangement of grains caused by gravity and metamorphism (McClung & Schaerer, 2006).

As the density of snow increases the hardness of the snow increases. Multiple studies have compared snow density to snow hardness with the use of the Swiss rammsonde (Bull, 1956; Keeler & Weeks, 1968; Martinelli, 1971). All three studies concluded the relationship between the ram hardness and snow density in dry snow resulted in a relation of the form:

$$logR = a + b\rho \qquad (1)$$

Where R is the ram hardness measured in kg, ρ is measured in kg/m^3, a and b are fitting constants the authors' used based on their observations (Bull, 1956; Keeler & Weeks, 1968; Martinelli, 1971).

In 1956, Gold carried out an experiment to determine the compressive strength of snow. For snow hardness measurements Gold used the National Research Council Type Snow Hardness Gauge, as seen in Figure 1.11. The gauge utilizes a circular plate and a spring-loaded rod inserted against the flat vertical face of a snow profile wall. Comparing snow hardness (H) to snow densities (ρ) in dry snow ($200 \leq \rho \leq 400$ kg/m^3) Gold found the relationship to be:

$$H = \left(3.55 \times 10^{-9} \frac{Pa}{(kg/m^3)^4}\right) \rho^4 \qquad (2)$$

Where H is measured in Pa and ρ is measured in kg/m^3 (Gold, 1956).

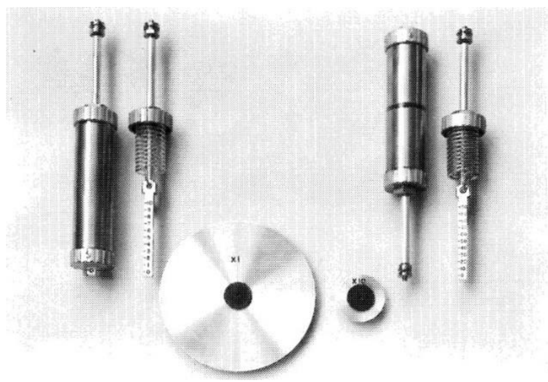

Figure 1.11. National Research Council Type Snow Gauge (aka. Canadian Gauge) used to measure snow hardness (Pearce & Gold, 1951).

In 1960 Kinosita, developed an instrument to measure the hardness of snow as seen in Figure 1.12. The instrument utilized placing a circular metal plate, C, on top of the snow surface attached to a rod, A, and small cylinder, B, at the base. A brass cylinder, m, with a hole through the center to pass through the rod could be held by the operator's hand a distance, h, above the small cylinder and then released to collide with the small cylinder and pushing the apparatus some distance, d, into the snow. Similarly, to Gold's experiment in 1956, Kinosita found a relationship between snow hardness and snow density in dry snow to be:

$$H = \left(1 \times 10^{-11} \frac{Pa}{(kg/m^3)^4}\right) \rho^4 \qquad (3)$$

Where H is measured again in Pa and ρ is in kg/m^3 (Kinosita, 1960).

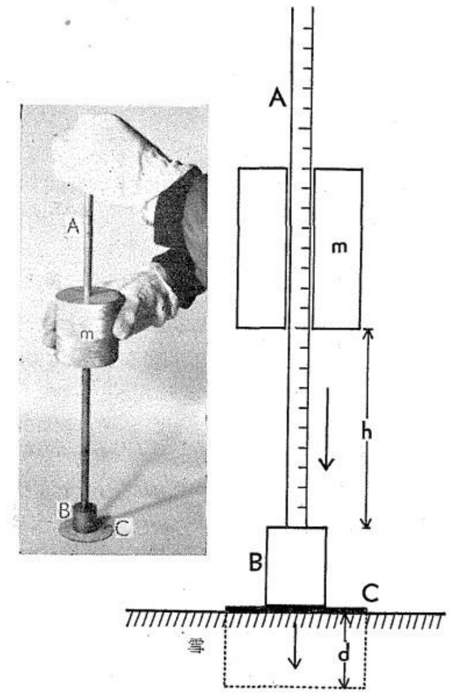

Figure 1.12. Snow hardness gauge developed and used by Kinosita (Kinosita, 1960).

In 1998, Takeuchi et al. utilized a digital push-pull force gauge with a circular plate (diameter of 14 mm) to measure the hardness of snow as seen in Figure 1.13. Snow hardness measurements were taken by pushing the gauge horizontally into the snow pit wall. By taking side by side snow hardness and snow density measurements in dry snow of fine grain size (E < 0.5 mm) they found the relationship:

$$H = \left(1.3 \times 10^{-10} \frac{Pa}{(kg/m^3)^4}\right) \rho^4 \qquad (4)$$

Where H is measured in Pa and ρ is measured in kg/m^3 (Takeuchi et al., 1998). Comparing snow hardness to snow density in wet snow resulted in non-uniform hardness values. The non-uniform hardness values are due to a heterogenous infiltration of meltwater (Takeuchi et al., 1998).

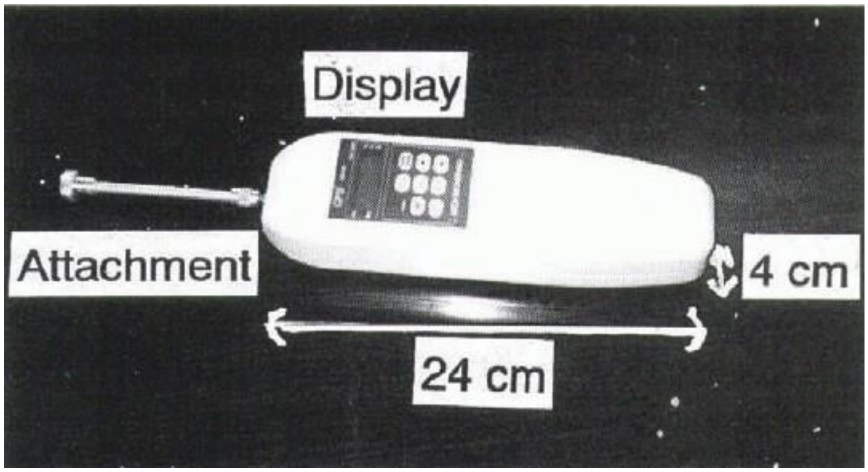

Figure 1.13. Digital push-pull force gauge adapted for snow hardness measurements (Takeuchi et al., 1998).

Similarly, to Takeuchi et al, Holler and Fromm in 2010 used a digital push-pull force gauge and found a relationship between snow hardness and snow density in dry snow to be:

$$H = \left(3.04 \times 10^{-6} \frac{Pa}{(kg/m^3)^4}\right) \rho^4 \qquad (5)$$

Where H is measured in Pa and ρ is measured in kg/m^3 (Höller & Fromm, 2010).

In 2000, Geldsetzer and Jamieson looked at snow profile data consisting of 5,411 snow layers taken in the mountains of Western Canada to estimate dry snow density from grain form and hand hardness. Wet snow was not included in analysis due to wet grains being dependent on liquid water content and exhibiting unacceptably large error values (Geldsetzer & Jamieson, 2000). As the hand hardness test utilizes objects of different surface areas (1 finger, 4 fingers, fist…) they created a step-wise hand hardness index (Fist = 1, Four Fingers = 2, etc.) which scales as the area of the probe. During the study they measured the approximate surface areas of the hand hardness classes and using the force of 10 to 15 N approximated the hardness of each class. The approximate surface areas and hardness of each class from Geldsetzer and Jamieson are seen in Table 1.2. The surface areas decrease exponentially as the hand hardness goes from fist to 4 fingers to 1 finger to pencil to knife.

Table 1.2. Average surface areas and hardness for hand hardness classes (Geldsetzer & Jamieson, 2000).

Hand Hardness	Area (cm2)	Hardness (kN/m2)
Fist	82	1.5
Four Fingers	22.5	5.6
1 Finger	5	25
Pencil	0.64	195
Knife	0.15	833

For most snow grain types (PP, DF, FC and DH) they found that the density to hand hardness conformed to the linear equation:

$$\rho = a + bh \qquad (6)$$

Where ρ is measured in kg/m^3, h is the (unitless) hand hardness index, a and b are fitting constants the authors' used based on their observations.

However, for rounded grain forms, the density to hand hardness conformed well to the non-linear equation:

$$\rho = a + bh^c \qquad (7)$$

Where ρ is measured in kg/m^3, h is the (unitless) hand hardness index, a, b, and c are fitting constants the authors' used based on their observations (Geldsetzer & Jamieson, 2000). In 2014, Kim and Jamieson updated the snow layer database, which tripled the amount of snow layers to over 15,000 layers of dry snow. With the updated data base, the authors' found that a multivariable linear regression worked best to estimate the density of snow with the relation being:

$$\rho = ah + bE + c \qquad (8)$$

Where ρ is measured in kg/m^3, h is the (unitless) hand hardness index, E is the grain size in mm, a, b, and c are fitting constants the authors' used based on their observations (Kim & Jamieson, 2014).

Looking at snow science literature shows that researchers have been comparing snow density to snow hardness since the 1950s. Due to wet snow grains being dependent on liquid water content the studies determined there was not a significant correlation between hardness and density in wet snow. These studies illustrate the density of dry snow can be estimated by measuring the hardness of the snow. With the addition of grain form and snow hardness the estimations of density will gain accuracy.

The BHG has been used to correlate the hardness of snow with snow density. In 2011, Borstad and McClung found a positive correlation (Spearman's rank correlation coefficient is 0.89, p-value < 0.01, n = 628) between blade hardness and density measurements. The density measurements were paired with single blade hardness measurements from 24 snow profiles during the 2007-08 and 2008-09 winter seasons (Borstad & McClung, 2011). In 2013, Buhler also found a positive correlation (Spearman's rank correlation coefficient is 0.62, p-value < 0.05, n = 27) (Buhler, 2013). The research in this thesis continued searching for a relation between blade hardness and density.

Calibration of Hand Hardness Test

In 1950, de Quervain introduced the hand hardness test with five classes. These classes were correlated to the Swiss rammsonde and relative snow hardness (de Quervain, 1950). Table 1.3 shows the correlated results that de Quervain set.

The Commission of Snow and Ice (ICSI) of the International Association of Hydrology (IASH) published the first issue of "The International Classification for Snow (with special reference to snow on the ground)" in 1954. The commission describes snow hardness as the correlation between the measurements from a particular hardness instrument and the combination of the compressive yield strength, tensile strength, and shear strength at zero normal stress of snow (Schaefer et al., 1954).

The United Nations Education, Scientific and Cultural Organization (UNESCO), IASH and World Meteorological Organization (WMO) published "Seasonal Snow Cover" in 1970, to update the 1954 international classification of snow. This updated version related snow hardness to the Swiss rammsonde and the hand hardness test. The standard penetration force for the hand hardness test was set at a force of 50 N (International Association of Scientific

Hydrology et al., 1970). This resulted in a new international standard for the hand hardness test being correlated to the Swiss rammsonde as seen in Table 1.3.

The International Commission on Snow and Ice (ICSI) of the International Association of Scientific Hydrology published the third issue of "The International Classification for Seasonal Snow on the Ground" in 1990. Ice was added as a sixth class to the hardness categories with no correlation to the hand hardness scale, Swiss rammsonde or magnitude of strength. The standard penetration force for the hand hardness test was maintained at a force of 50 N (S. Colbeck et al., 1990).

The latest edition of "The International Classification for Seasonal Snow on the Ground" was published in 2009 by the International Hydrological Programme of the UNESCO. In 2009 the standard penetration force for the hand hardness test was set at a force of 10-15 N, which was the standard in North America (McClung & Schaerer, 2006). With the new international penetration force standard, a new correlation between hand hardness and Swiss rammsonde hardness was set as seen in Table 1.3.

Table 1.3. Correlation of Hand Hardness Test Over Time (S. Colbeck et al., 1990; de Quervain, 1950; Fierz et al., 2009; International Association of Scientific Hydrology et al., 1970).

	Year	**1950 De Quervain's**	**1970 IASH**	**1990 IASH**	**2009 IASH**	
Hand Hardness Scale	Descriptive Term	Swiss Rammsonde (kg)	Swiss Rammsonde (N)	Order of Magnitude Strength (Pa)	Swiss Rammsonde Range (N)	Swiss Rammsonde Median (N)
Fist (F)	Very soft	0 – 3	0 – 20	0 - 10^3	0 – 50	20
4 Fingers (4F)	Soft	3 – 15	20 – 150	10^3 - 10^4	50 – 175	100
1 Finger (1F)	Medium	15 - 50	150 – 500	10^4 - 10^5	175 – 390	250
Pencil (P)	Hard	50 – 150	500 – 1000	10^5 - 10^6	390 – 715	500
Knife (K)	Very hard	> 150	> 1000	> 10^6	715 – 1200	1000
Ice	Ice				>1200	>1200

During the initial prototyping of the SnowMicroPen (SMP), a motor controlled, high spatial resolution penetrometer, Schneebeli and Johnson compared SMP hardness profiles with the hand hardness test. Comparing the two methods illustrated that layers of snow with high variability of snow hardness determined by the SMP are difficult to judge by the hand hardness test (Schneebeli & Johnson, 1998). During the 2000/01 and 2001/02 winter seasons, Pielmeier and Johnson, carried out seven snow profiles recording adjacent hardness profiles with the hand hardness test, Swiss rammsonde and the SMP. The SMP proved to yield the highest spatial and force resolution of the three methods. Snow hardness with gradual changes at layer boundaries were impossible to accurately measure with the hand hardness test but were possible with the SMP (Pielmeier & Schneebeli, 2003b). During the 2007/08 and 2008/09 winter seasons, Höller and Fromm (2010) carried out a few tens of snow profiles recording adjacent hardness profiles with the hand hardness test, a digital force gauge and the SMP. They found that for each hand hardness index there was variability in the measured values of hardness by the SMP and the digital force gauge. The variability of hardness measurements within a given hand hardness index illustrates the biases of the hand hardness test. Utilizing a digital force gauge will show the variations of hardness in a specific snow layer.

Borstad and McClung compared the first iteration of the BHG with the hand hardness test. By comparing 520 BHG measurements with their respective hand hardness measurements resulted in considerable overlap between blade hardness and hand hardness classes (Borstad & McClung, 2011). The first iteration of the BHG was unable to measure soft snow with a hand hardness softer than 4F-. The Parks Canada study with a more current iteration of the BHG during the 2016-17 winter compared 685 BHG measurements with their respective hand hardness measurements. This study resulted in considerable overlap between blade hardness and hand hardness classes (Pogue et al., 2018). Results from the Parks Canada study are seen in

Table 1.4 comparing the blade hardness measurements with the hand hardness test.

Table 1.4. BHG measurements compared to hand hardness measurements during Parks Canada Study (Pogue et al., 2018).

Hand Hardness	Number of measurements	Mean (N)	Median (N)	Std. Dev. (N)
Fist (F)	102	0.54	0.39	0.45
4 Fingers (4F)	87	0.79	0.54	1.1
1 Finger (1F)	168	1.6	1.2	1.6
Pencil (P)	283	6.5	4.4	6.7
Knife (K)	45	20	24	17

Ever since the hand hardness test was first introduced by de Quervain in 1950 it has been calibrated against a variety of hardness instruments including, the Swiss rammsonde, the SMP, various types of digital force gauges and the BHG. The hand hardness test is subjective based on the person using it, varying force of insertion and varying size of hand. Using technologies such as the BHG, the human biases of the hand hardness test may be eliminated resulting in the ability to measure snow hardness over time with multiple operators.

Chapter 2. Methods

Data for this study was collected during the 2020/21 and 2021/22 winter seasons. This section will discuss the methods in taking the data with respect to study plot locations and equipment used. Furthermore, the details of each research component (insertion rate, gauge replication, orientation of the gauge and comparison between blade hardness measurements with hand hardness measurements, snow density measurements and extended column test results) will be discussed with respect to data acquisition and analysis.

Study Plots

The first field season was from November 2020 to May 2021 and the second field season was from November 2021 to May 2022. The primary study plots for the 2 field seasons were in the Kicking Horse Mountain Resort ski area tenure and surrounding backcountry in Golden, B.C, Canada. Four study plots were sanctioned off with polypropylene rope and 2 m tall bamboo posts (rope and bamboo courtesy of Kicking Horse Mountain Resort) to conserve an undisturbed snowpack. The four study plots were located at 51°17’24.60"N 117°4’59.40"W (Study Plot 1 Elevation: 2120 m), 51°16’34.91"N 117°4’53.23"W (Study Plot 2 Elevation: 2220 m), 51°17’1.62"N 117°4’26.58"W (Study Plot 3 Elevation: 2060 m), and 51°17’3.22"N 117°4’24.11"W (Study Plot 4 Elevation: 2050 m). The study plots vary in characteristics with regards to elevation and sheltering to wind and sun. A Google Earth image showing the locations of the four primary study plots is seen in Figure 2.1 with a picture of “Study Plot 1” seen in Figure 2.2.

Figure 2.1. Google Earth image of the four primary study plots located at Kicking Horse Mountain Resort and the surrounding backcountry.

Figure 2.2. Photo of Study Plot 1 located at 51°17’24.60"N 117°4’59.40"W, Elevation: 2120 m, in the Kicking Horse Mountain Resort backcountry (photo by author).

Further field study plots were used throughout the mountains of B.C and Alberta in the Purcell Mountain Range (Golden, B.C), Selkirk Mountain Range (Glacier National Park), Okanagan Highlands (Big White Ski Area), the Canadian Rockies and Coast Range (Whistler, B.C). The study plots across B.C and Alberta are seen in Figure 2.3. Study plots were selected to be in undisturbed areas and based on the objective in question. The purpose of using multiple field plots in multiple locations is to show that the BHG can be used in varying snowpacks. Snow climates are characterized as maritime, transitional, and continental throughout the mountains of Western Canada (McClung & Schaerer, 2006). Utilizing the multiple field plots in this research allowed the use of the BHG in all three snow climates.

Snow profiles carried out in the study plots followed the observation and recording standards outlined by the Canadian Avalanche Association (Canadian Avalanche Association, 2016b). Further observations were taken with the use of the blade hardness gauge.

Equipment

The blade hardness gauges (BHG) used in this study are produced by Fraser Instruments Ltd. The blade is 0.6 mm thick with a width of 10.0 cm. The BHG has a range of 0 – 50 N and is precise to 0.05 N. Figure 2.4 shows a BHG produced by Fraser Instruments Ltd.

Snow temperatures were taken with a Taylor 9842 digital thermometer as seen in Figure 2.5 and Figure 2.6. The manufacturer states the thermometer is accurate to ± 0.06°C from -8 to 110°C and ± 2.00°C above 110°C and below -18°C. To keep temperature measurements consistent only one thermometer was used throughout the study. On a weekly basis the thermometer was calibrated to 0°C in an ice-water mixture.

Snow grain forms were identified and measured using an aluminum crystal screen made by Backcountry Access and a 17 times magnification loupe made by Carson as seen in Figure 2.7. Snow grains were placed on the screen, either on the 1 mm or 3 mm grid and viewed through the loupe to be identified and measured.

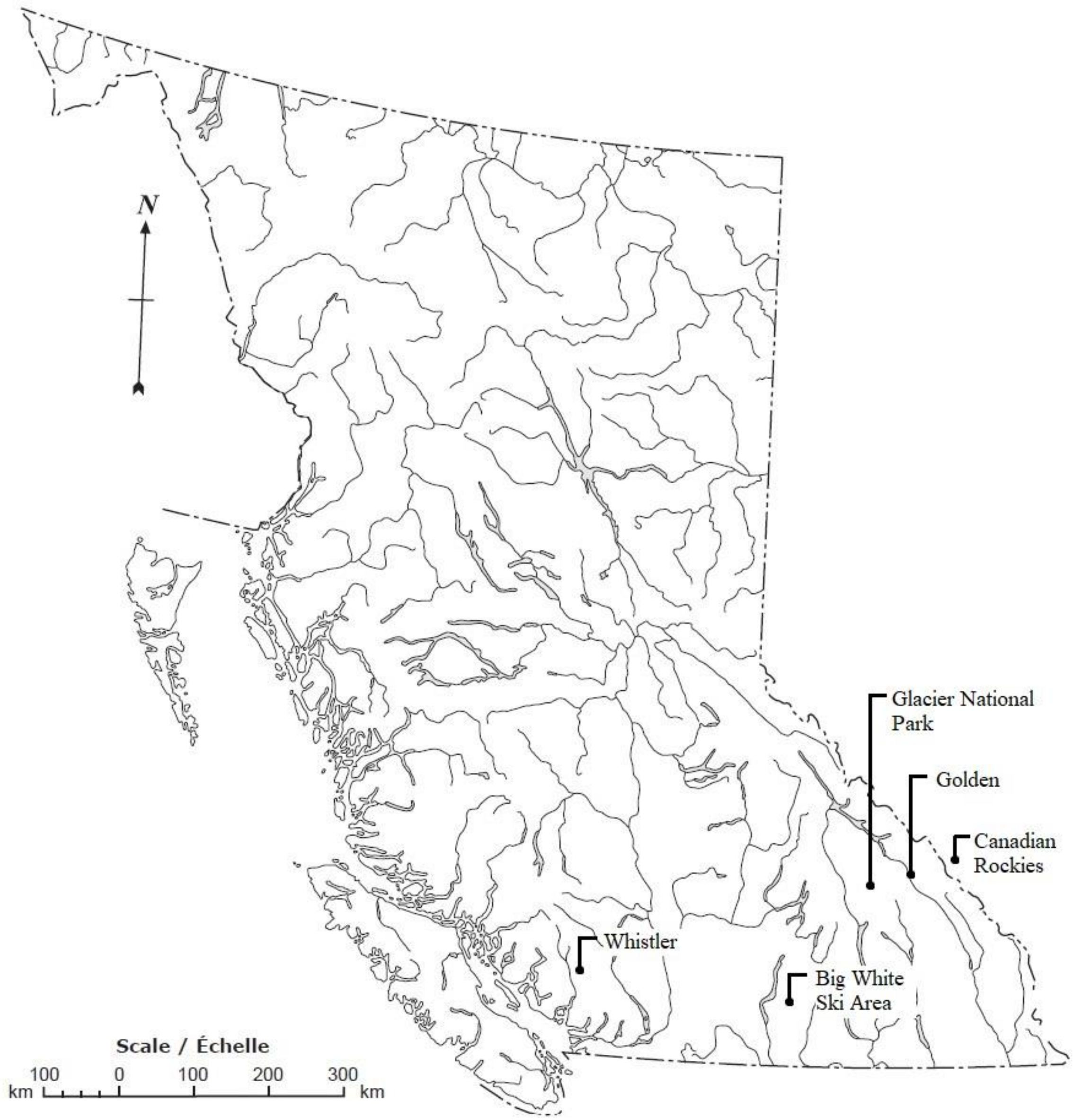

Figure 2.3. Study plot locations on a map of British Columbia

Figure 2.4. Blade Hardness Gauge made by Fraser Instruments Ltd. (photo by author).

Figure 2.5. Front view of Taylor 9842 digital thermometer (photo by author).

Figure 2.6. Side view of Taylor 9842 digital thermometer (photo by author).

Figure 2.7. Backcountry Access aluminum crystal screen and Carson loupe used for snow crystal identification and sizing (photo by author).

Further equipment used included standard avalanche safety equipment (transceiver, shovel, and probe), skis, and ski touring equipment for access to study plots. Snow profiles and observations were recorded in the field into all weather, Rite in the Rain, notebooks.

Insertion Rate

Objectives

Determine if there is a difference in recorded snow hardness by the BHG between fast (≈ 10 cm/s) and slow (≈ 1-3 cm/s) insertion rates in snow. The slow insertion rate will be approximately 1 order of magnitude less than the fast insertion rate.

If there is a difference between fast and slow insertion rates the goal is to determine which one is more consistent with respect to measuring snow hardness. This will be important to know so that measurements taken with the BHG will be as consistent as possible.

Experiment

The BHG was inserted with a fast (≈ 10 cm/s) insertion rate into the snow with an angle parallel to the slope and the measurement was recorded at the time taken. The same BHG then was inserted with a slow (≈ 1-3 cm/s) insertion rate into the same depth of snow at the same angle as the previous measurement (parallel with the slope) with a spacing of roughly 2 cm apart and the measurements recorded at the time taken. The insertion rate speeds were calibrated by using a timer, and a ruler as speed is the measure of the distance covered in a given amount of time. These calibrations were carried out inside by the researcher before going out into the field. In the field the insertion rates were subjectively judged by the researcher. Figure 2.8 illustrates the spacing of the BHG measurements that were taken.

To determine the consistency of fast versus slow measurements, 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 2.9 illustrates the spacing of BHG measurements that were taken.

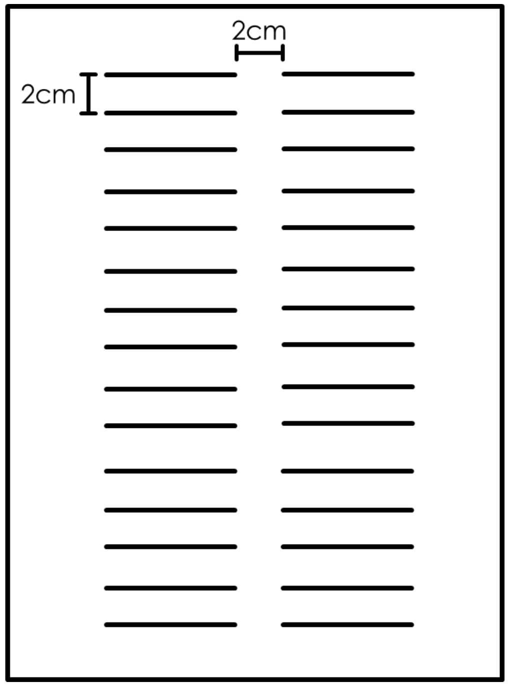

Figure 2.8. Schematic of the spacing of blade hardness measurements in relation to the insertion rate objective.

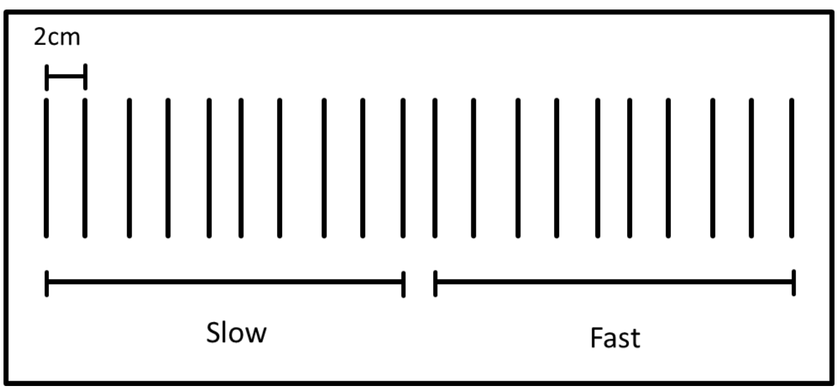

Figure 2.9. Schematic of the spacing of blade hardness measurements in relation to the consistency of insertion rate objective.

Gauge Replication

Objectives

As the BHG is a new technology it is imperative that a 3rd party compares the replication of two BHGs to see that the gauges reliably report the same snow hardness in the snowpack. One BHG was provided by the manufacturer, and one was provided by Parks Canada. No financial funding has been provided by the BHG manufacturer. If the BHG is to be used as a new standard by avalanche safety operations, it is important to know that the individual gauges correspond to one another.

Experiment

Two BHGs were used throughout the study ("A" from the manufacturer, "B" from Parks Canada and both were manufactured by Fraser Instruments Ltd.) To test replication without snow, the gauges were held perpendicular to each other, the blades placed together and pushed inwards. The BHG measurements were then recorded for each gauge. To test replication in the snowpack, the gauges were inserted into the same depth of snow at the same angle to each other (parallel with the slope) with a spacing of roughly 2 cm apart and the measurements recorded at the time taken. All BHG measurements taken in the snowpack utilized an insertion rate of approximately 10 cm/s subjectively judged by the researcher.

Orientation of the Blade Hardness Gauge

Objectives

The snowpack increases in thickness throughout the winter season due to accumulation of snow, there are distinct layers in the snowpack with thickness ranging from 0.1 mm to larger than 30 cm. The current suggested method of measuring the snow hardness with the BHG utilizes inserting the wide part of the blade into the snow parallel to the slope. To get an average blade hardness covering 10 cm vertically, the wide part of the blade will be inserted into the snow perpendicular to the slope. The vertical measurements (perpendicular to slope) will be compared with 6 corresponding horizontal measurements (parallel to slope). Measurements taken in the field must be accurate and taken in a timely manner to be effective.

Utilizing vertical measurements could reduce the time in the field for avalanche technicians and forecasters.

Experiment

The locations of the layer boundaries were determined using visual and physical techniques in excavated snow profiles. Homogenous layers in the snowpack that were 10 cm or more in height had six horizontal (slope parallel) BHG measurements versus one vertical (slope perpendicular) BHG measurement compared. The horizontal measurements were taken with 2 cm vertical spacings for a total vertical height of 10 cm. Using the BHG vertically, the gauge took a measurement with a total vertical height of 10 cm. The horizontal and vertical measurements were taken with a spacing of roughly 2 cm apart and recorded at the time taken. Figure 2.10 illustrates the spacing of the BHG measurements that were taken. All BHG measurements were taken with an insertion rate of approximately 10 cm/s subjectively judged by the researcher.

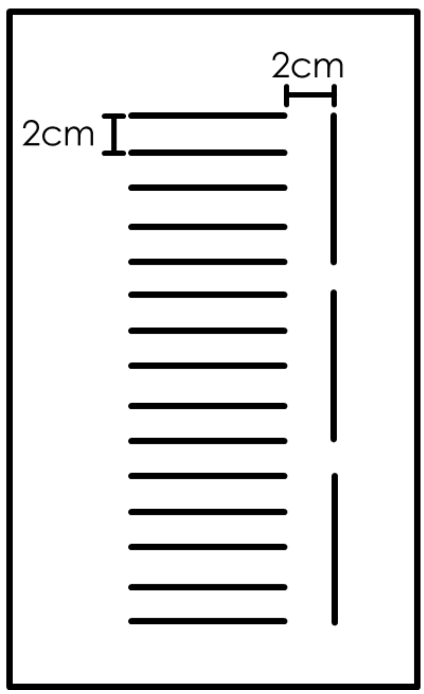

Figure 2.10. Schematic of the spacing of blade hardness measurements in relation to the orientation of the blade hardness gauge.

To assess the horizontal versus vertical measurements across any snowpack (non homogenous) the procedure for the homogenous layers was replicated without the need of isolating specific layers. The measurements were taken from the top to the bottom of the snowpack.

Blade Hardness Gauge versus Snow Density

Objectives

BHG measurements will be compared to snow density measurements in paired sets in the snowpack to see if there is a correlation between the two. Snow density measurements in the field can be cumbersome but is useful for determining the water equivalency of a snowpack or calculating the load over a given buried weak layer. By finding a relation between the BHG and density could produce an efficient tool for estimating densities when there is limited time.

Experiment

The snow mass was measured using a metal cylinder (length 8.8 ± 0.1 cm, radius 1.9 ± 0.1 cm, volume 100 ± 12 cm^3), a metal holder for the cylinder and a scale (Pesola Micro-Line 20100 scale, precision ± 0.3 % of load, reading error ± 1 g). The snow density was calculated using the relation:

$$\rho = \frac{m}{V} \qquad (9)$$

BHG measurements were taken roughly 2 cm adjacent to the snow density measurements. Figure 2.11 illustrates the spacing of the BHG and snow density measurements. A photo of the snow density apparatus is seen in Figure 2.12. All BHG measurements were taken with an insertion rate of approximately 10 cm/s subjectively judged by the researcher.

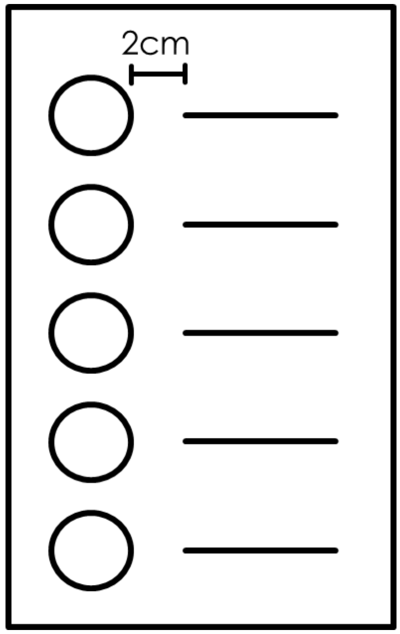

Figure 2.11. Schematic of the spacing of blade hardness and snow density measurements.

Figure 2.12. Snow density apparatus including the Pesola Scale and 100 cm^3 metal cylinder (photo by author).

Snow density with corresponding BHG measurements were taken at multiple field study plots in multiple climate zones and different times in the field season to gather densities of a variety of snow grains. The snow grains consist of precipitation particles, decomposing fragments, faceted crystals, and rounded grains. The snow grains were identified and measured in size using the crystal screen and magnifying loupe seen in Figure 2.7.

Blade Hardness Gauge versus Hand Hardness Test

Objectives

Blade hardness measurements will be taken in correspondence to respective hand hardness profiles to quantitatively measure the hand hardness scale. The hand hardness test is known to be influenced by human biases such as failure to apply 10-15 N of force and different sizes of hands. Replication of the hand hardness test and BHG will be explored amongst users in the same snow profile. The BHG could become a new standard in measuring snow hardness. If there is good replication amongst users with the BHG it could be used to accurately measure the hardness of snow over time amongst multiple users. By creating a BHG to hand hardness scale the gauge could be used as a teaching tool to introduce the hand hardness test to new users. The BHG could also be used as a calibrating tool to ensure the technician is consistently applying 10-15 N of force into the snowpack when applying the hand hardness test.

Experiment

The locations of the layer boundaries were determined using visual and tactile techniques in excavated snow profiles. The hand hardness was recorded for each layer by an avalanche technician. BHG measurements were taken roughly every 2 cm in the layers by the lead researcher to obtain consistent BHG measurements. All BHG measurements were taken with an insertion rate of approximately 10 cm/s subjectively judged by the researcher. For "Pencil" hardness levels the avalanche technician used the blunt end of a standard pencil, seen in Figure 2.13. For "Knife" hardness levels the avalanche technician used the sharp end of a SOG folding knife, seen in Figure 2.14.

Figure 2.13. Standard pencil used during the hand hardness test (photo by author).

Figure 2.14. SOG folding knife used during the hand hardness test (photo by author).

To test the reproducibility of the hand hardness test and the BHG, avalanche technicians took corresponding hand hardness and BHG measurements one after another (the subsequent technician did not know the measurements that the previous technician measured to maintain independence). The technicians were told to take BHG measurements roughly every 2 cm in the layers with a fast consistent insertion rate of approximately 10 cm/s. These sets of measurements were taken in the same snow profile with minimal time in between technicians, to reduce the effects of weather, and minimal spacing, to reduce the effects of spatial variability in the snowpack.

Avalanche technicians used in this study were required to have the Canadian Avalanche Association Avalanche Operations Level 1, 2 or 3 certification.

Blade Hardness Gauge versus Extended Column Test

Objectives

Blade hardness measurements will be taken with corresponding extended column tests (ECT) to search for a relationship between the hardness of the slab, weak layer, and bed surface in relation to ECT propagation results. If a relation is found between blade hardness measurements and ECT results this could result in less time carrying out ECTs and benefit future research with regards to snow hardness and fracture propagation.

Experiment

Extended columns tests (ECT) were carried out in relation to the CAA OGRS (Canadian Avalanche Association, 2016b) at various field plots. The hardness of the snow was measured using the BHG in roughly 2 cm increments starting from the top of the snowpack to 30 cm below the weak layer in question with respect to the extended column test. Further BHG measurements were taken of the weak layer, 1 cm above the weak layer and 1 cm below the weak layer. All BHG measurements were taken with an insertion rate of approximately 10 cm/s subjectively judged by the researcher. Along with hardness, measurements of crystal shape, grain size, slope aspect, slope incline, and exact location was taken at each field site.

Statistical Analysis

During the field research the data was written down into “Rite in the Rain” notebooks. The data was then transferred to Microsoft Excel spreadsheets. Statistical analysis was carried out in Microsoft Excel or Minitab statistical software. Blade hardness measurements and density measurements are ratio and continuous data. Hand hardness measurements and extended column test results are ordinal and continuous data. All data collected were first tested for normality with either the Ryan-Joiner test ($n < 25$) or the Kolmogorov-Smirnov test ($n > 25$).

For paired tests (insertion rate, gauge replication and gauge orientation) the Wilcoxon signed-rank test was used to test if there is a statistically significant difference from zero in the median of the distribution of differences of the paired measurements. The Spearman’s rank correlation test was used to see if blade hardness measurements correlate with snow density. Linear and nonlinear regression analysis will be used to search for a relation between snow density and the snow hardness. To compare BHG measurements with respect to their corresponding hand hardness scale, the Kruskal-Wallis test and the Mann-Whitney test will be utilized to compare the respective medians. The Kruskal-Wallis test will be used to compare three or more hand hardness levels (such as 4F-, 4F and 4F+) while the Mann-Whitney test will be used when comparing two hand hardness levels (such as F and 4F).

To evaluate the hand hardness reproducibility, direct observations of each avalanche technician were compared to one another. To evaluate the BHG reproducibility, a minimum of three BHG measurements were needed by each avalanche technician per snow layer. The BHG measurements were then compared using either the Two-sample t-test (parametric) or the Mann-Whitney test (non-parametric) depending on the distribution of the data. For both the Two-Sample t-Test and the Mann-Whitney Test a significance threshold of $p \leq 0.05$ was used. If the comparison resulted in $p > 0.05$ the data supports that the BHG measurements are in agreement of each other within current measurement precision.

The extended column test results were broken into two ordinal categories with respect to propagating the full 90 cm or less than 90 cm. The mean values of the BHG measurements with respect to the slab, weak layer and bed surface were then compared to the extended column test results with statistical Two-sample T-tests.

Chapter 3. Results

This chapter highlights the results of the data acquisition and analysis of each objective with the blade hardness gauge (BHG) as described in the introductory chapter. The results cover the insertion rate of the BHG, gauge replication, orientation of the BHG, and the comparison between blade hardness measurements with snow density, hand hardness measurements and extended column test results. The objective in question will be laid out with the measurements taken, and the statistical analysis used. Further discussion of the results with implications of using the BHG will be discussed in subsequent chapters.

Insertion Rate

Paired Measurements

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. A histogram illustrating the distribution of differences between the fast and slow insertion rates is seen in **Error! Reference source not found.**. The y-axis represents the frequency of measurements. The x-axis is the difference between fast and slow blade hardness measurements measured in N.

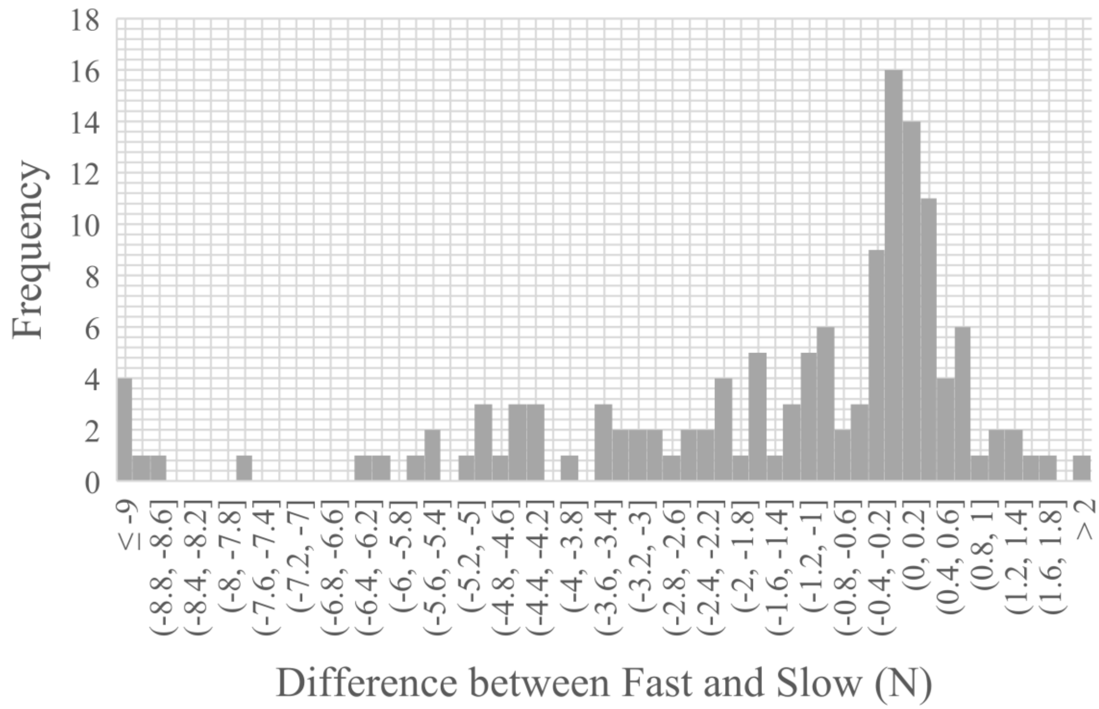

Figure 3.1. Histogram illustrating the distribution of differences between the fast and slow insertion rates of the blade hardness gauge into dry snow, n = 136.

Figure 3.1 shows that the data is heavily skewed to the left illustrating there is a difference between the fast and slow blade hardness measurements. Using the Kolmogorov-Smirnov Normality test resulted in non-normal distributions for the fast (KS = 0.22 and $p < 0.01$) and slow (KS = 0.20 and $p < 0.01$) insertion rates. 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 significant difference from zero in the median of the distribution of differences between the fast and slow insertion rates.

Paired Snow Layers

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. A box and whisker plot comparing the means of the 11 trials is seen in Figure 3.2. The y-axis has the mean blade hardness values of the 10 BHG measurements in each trial, measured in N of force. The x-axis breaks the two box plots up into the different insertion rates (fast and slow). The shaded square represents the interquartile range (25-75%), the line in the shaded square represents the median and the whiskers represent the minimum and maximum ranges found in the 11 trials.

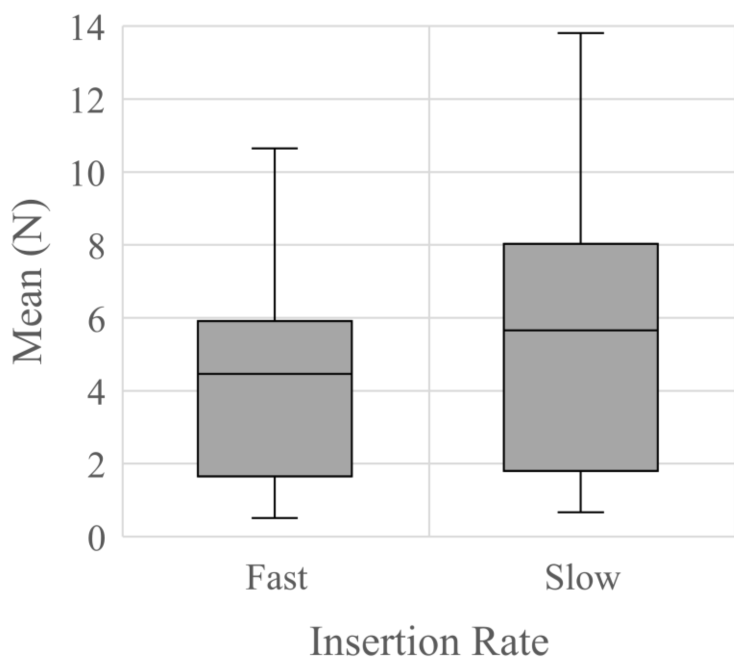

Figure 3.2. Box and whisker plot grouping the means of the 11 fast versus slow insertion rate trials.

Looking at the data illustrated in Figure 3.2 the fast insertion rate results in a smaller median value and a smaller interquartile range. This suggests a fast insertion rate results in a lower mean and median measurement than that with a slow insertion rate.

A box and whisker plot comparing the standard deviations of the 11 trials is seen in Figure 3.3. The y-axis has the standard deviation blade hardness values of the 10 BHG measurements in each trial, measured in N of force. The x-axis breaks the two box plots up into the different insertion rates (fast and slow). The shaded square represents the interquartile range, the line in the shaded square represents the median and the whiskers represent the minimum and maximum ranges found in the 11 trials.

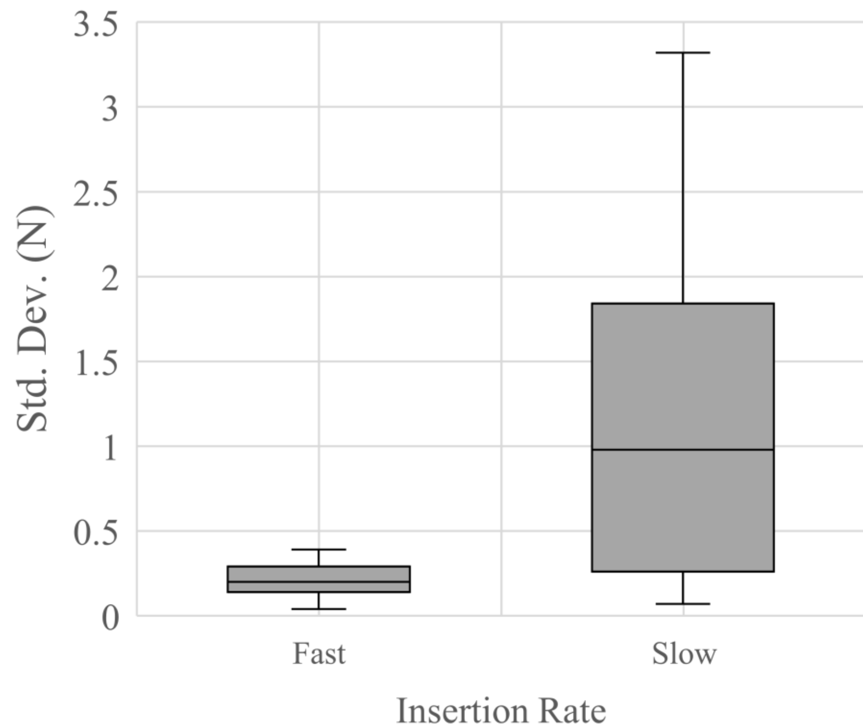

Figure 3.3. Box and whisker plot grouping the standard deviations of the 11 fast versus slow insertion rate trials.

Looking at the data illustrated in Figure 3.3 the fast insertion rate results in a smaller median value and a smaller interquartile range. This 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.

Using the Ryan-Joiner Normality test resulted in non-normal distributions for the fast (RJ = 0.92 and p = 0.046) and slow (RJ = 0.91 and p = 0.029) standard deviations. 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 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, in each trial, it is more consistent than the slow insertion rate.

Gauge Replication

A total of 250 pairs of BHG measurements with two different gauges (A-Manufacturer's BHG and B-Parks Canada's BHG) were compared against one another. The two gauges were held perpendicular to another and pressed together by the blade of each gauge. Figure 3.4 shows a scatterplot of the 250 in situ pairs. The x-axis represents the blade hardness measurements taken from Gauge A, the y-axis represents the blade hardness measurements taken from Gauge B both measured in N of force. The dashed trend line represents the linear regression analysis line.

Using linear regression analysis results in a coefficient of determination ($R^2 = 0.99$), a significance level, ($p < 0.01$), and a standard error of regression ($S = 0.10$). With a high coefficient of determination and a low standard error of regression there is a reasonable case

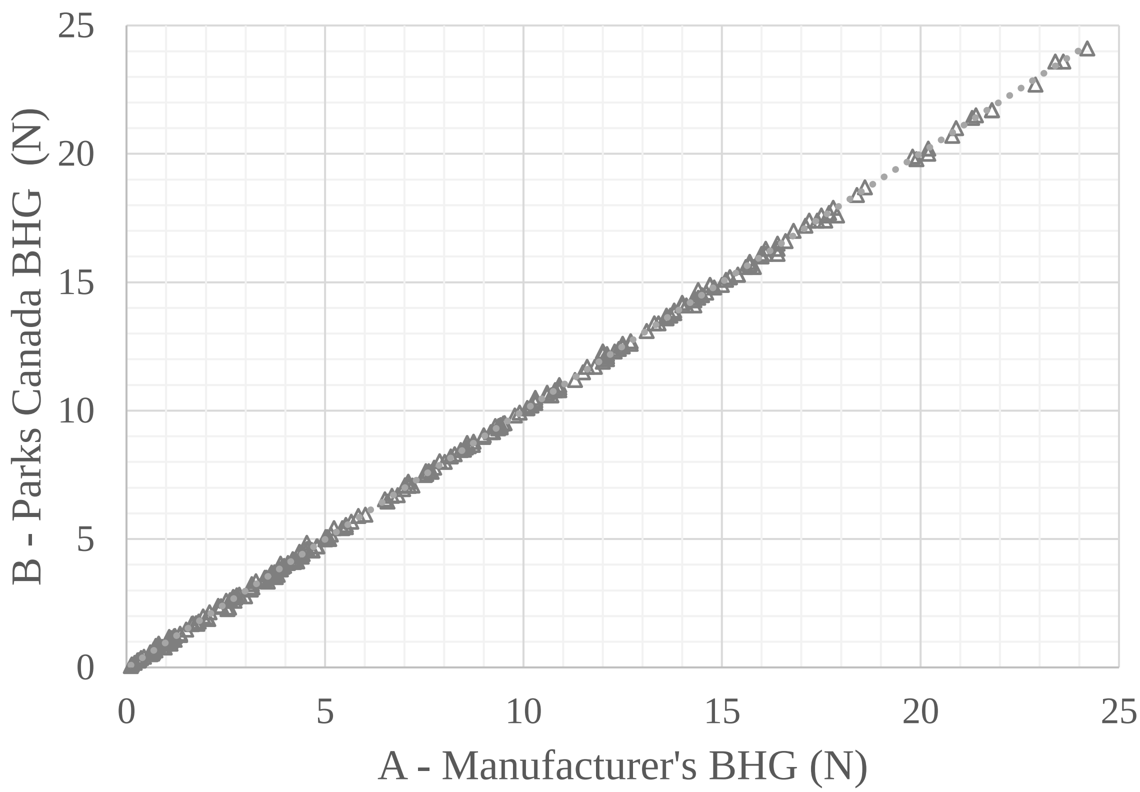

Figure 3.4. Scatterplot comparing Gauge A with Gauge B for purposes of replication. The dotted line is the best fit linear regression.

to conclude there is no significant difference between the two gauges. Using the Kolmogorov-Smirnov Normality test resulted in non-normal distributions for A (KS = 0.12 and $p < 0.01$) and B (KS = 0.12 and $p < 0.01$) gauges. Being paired and nonparametric, the Wilcoxon signed-rank test was used to compare the two gauges (WS = 10407.00, $p = 0.414$). The data supports there is no significant difference from zero in the median of the distribution of differences between the two BHGs. Figure 3.5 displays a histogram of the 250 paired differences between the BHGs. The distribution of differences is not skewed illustrating that there is no difference between the two BHGs.

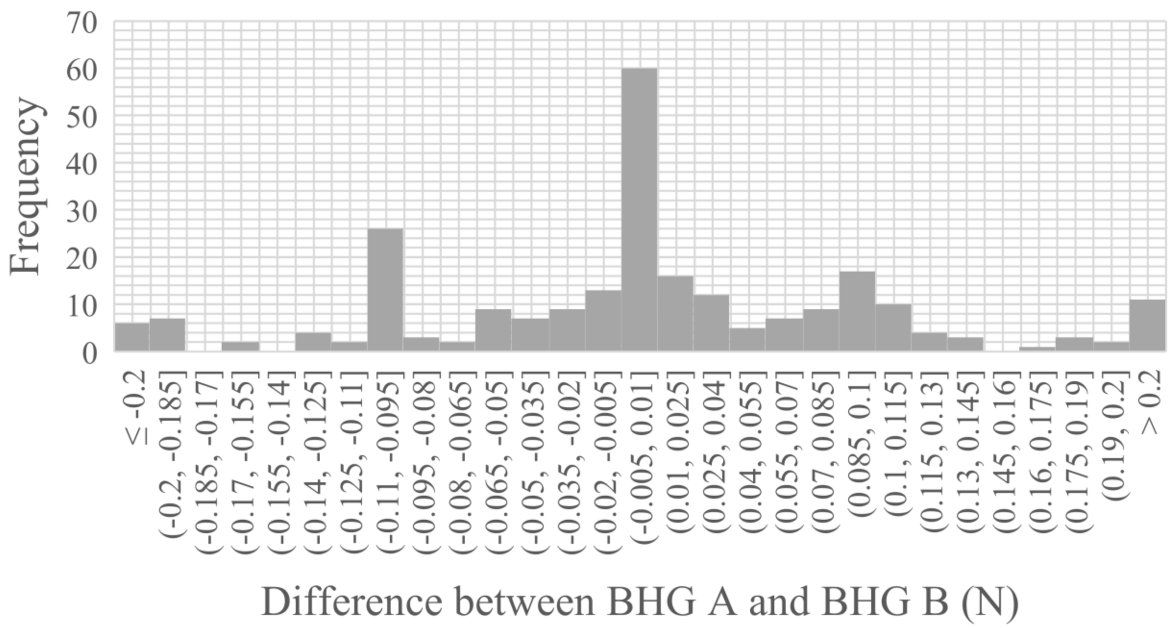

Figure 3.5. Histogram illustrating the distribution of differences between the blade hardness gauges' (A and B) paired measurements being held perpendicular to one another, n = 250.

A total of 678 in situ pairs of BHG measurements with two different gauges (A-Manufacturer's BHG and B-Parks Canada's BHG) were taken in snow profiles consisting of dry snow ranging in blade hardness 0.0 N to 24.1 N. Figure 3.6 shows a scatterplot of the 678 in situ pairs. The x-axis represents the blade hardness measurements taken from Gauge A, the y-axis represents the blade hardness measurements taken from Gauge B both measured in N of force. The dashed trend line represents the linear regression analysis line. The solid line represents a guide to the eye for exact replication.

Figure 3.6. Scatterplot comparing Gauge A with Gauge B for purposes of replication in the snowpack, n = 678. The dotted line is the best fit linear regression.

Using linear regression analysis results in a coefficient of determination ($R^2 = 0.92$), a significance level, ($p < 0.01$), and a standard error of regression ($S = 1.06$). With a high coefficient of determination and a low standard error of regression there is a reasonable case to conclude there is no significant difference between the two gauges.

Using the Kolmogorov-Smirnov Normality test resulted in non-normal distributions for A ($KS = 0.18$ and $p < 0.01$) and B ($KS = 0.17$ and $p < 0.01$) gauges. Being paired and nonparametric, the Wilcoxon signed-rank test was used to compare the two gauges ($WS = 107419.00$, $p = 0.464$). The data supports there is no significant difference from zero in the median of the distribution of differences between the two BHGs. Figure 3.7 displays a histogram of the 678 paired differences between the BHGs. The distribution of differences is not skewed illustrating that there is no difference between the two BHGs.

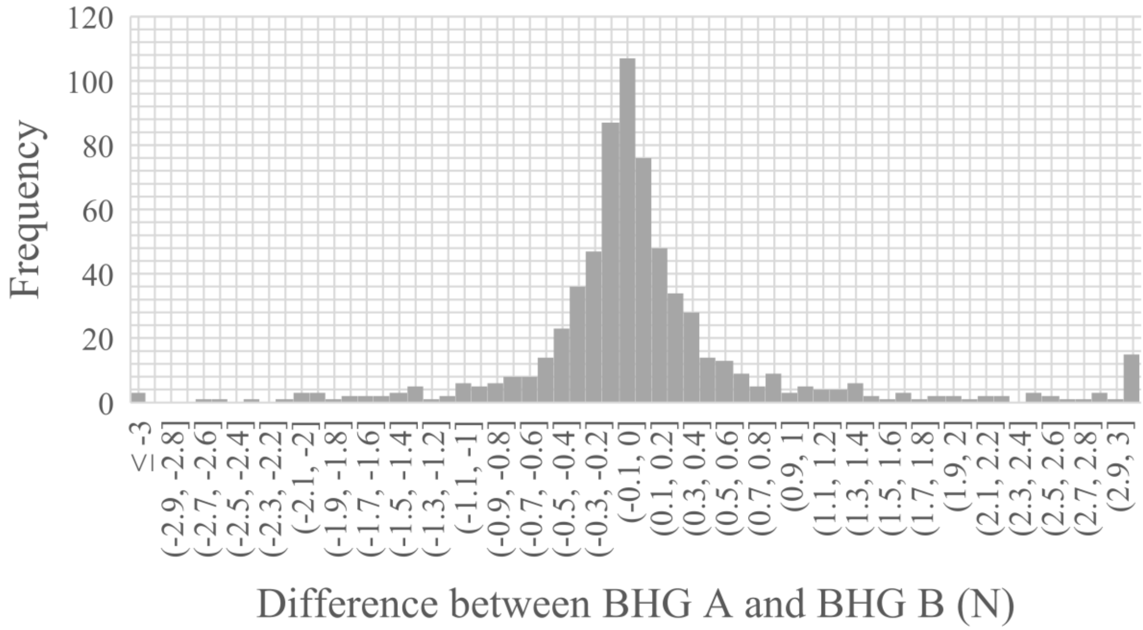

Figure 3.7. Histogram illustrating the distribution of differences between the blade hardness gauges' (A and B) paired measurements in dry alpine snow, n = 678.

Orientation of the Blade Hardness Gauge

Homogenous Snow Layers

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. Using the Kolmogorov-Smirnov Normality test resulted in non-normal distributions for vertical (KS = 0.205 and $p < 0.01$) and mean horizontal (KS = 0.207 and $p < 0.01$) measurements. 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 significant difference from zero in the median of the distribution of differences between the two BHGs. Figure 3.8 displays a histogram of the 186 paired differences between the vertical and mean horizontal blade hardness measurements in homogenous snow layers.

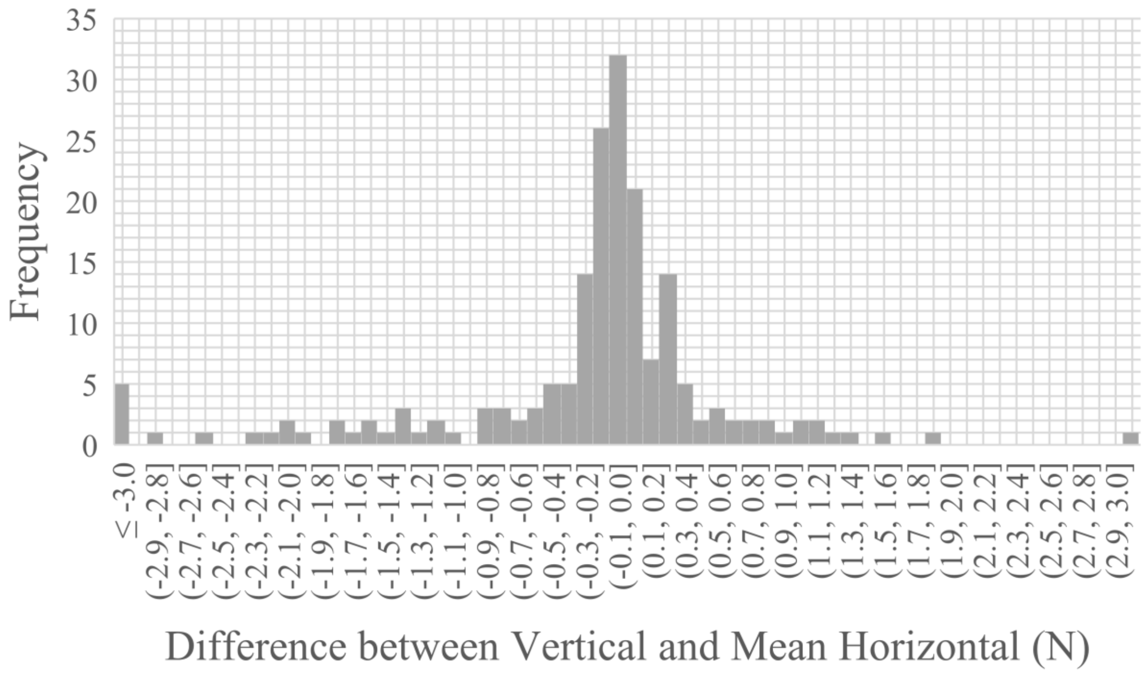

Figure 3.8. Histogram illustrating the distribution of differences between the vertical and mean horizontal blade hardness measurements (Difference = Vertical – Mean Horizontal) in homogenous snow layers, n = 186.

Entirety of the snowpack

232 vertical (slope perpendicular) BHG measurements (height of 10 cm) were compared with 232 mean horizontal (slope parallel) measurements (mean of six horizontal measurements spaced 2 cm apart for total height of 10 cm) in dry snow. Using the Kolmogorov-Smirnov Normality test resulted in non-normal distributions for vertical (KS = 0.175 and $p < 0.01$) and mean horizontal (KS = 0.176 and $p < 0.01$) measurements. Being paired and nonparametric, the Wilcoxon signed-rank test was used to compare the two gauges (WS = 9031.50, $p < 0.01$). The data supports there is a significant difference from zero in the median of the distribution of differences between the two BHGs. Figure 3.9 displays a histogram of the 186 paired differences between the vertical and mean horizontal blade hardness measurements in homogenous snow layers.

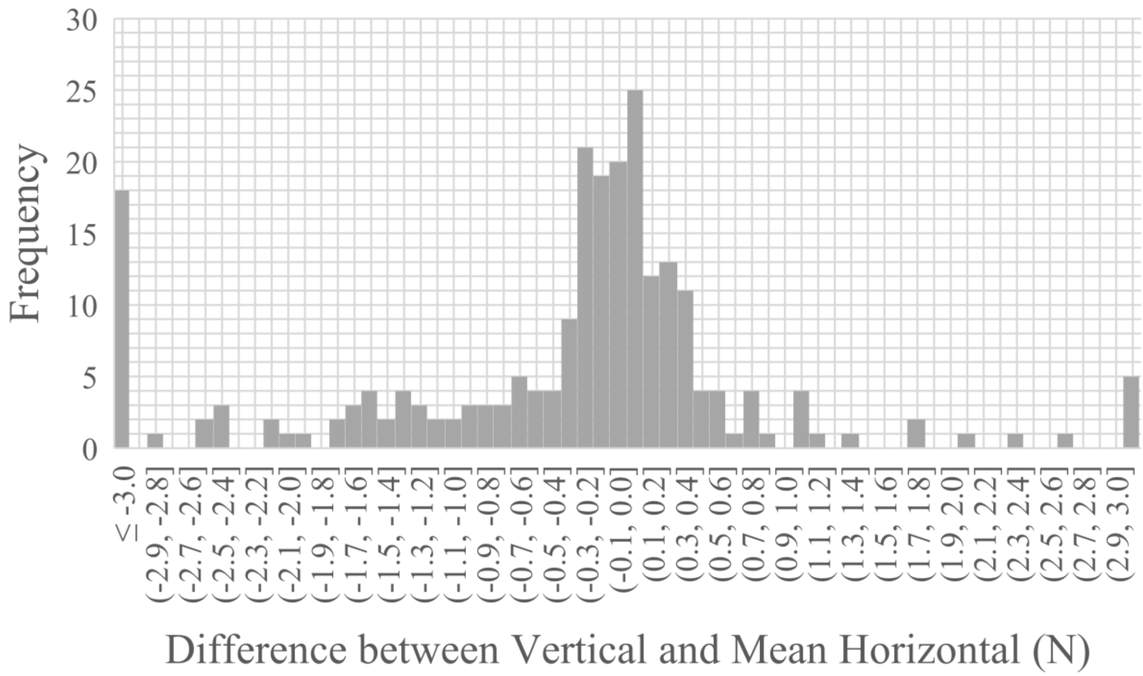

Figure 3.9. Histogram illustrating the distribution of differences between the vertical and mean horizontal blade hardness measurements (Difference = Vertical – Mean Horizontal) across the entire snowpack including homogenous and non-homogenous snow layers, n = 232.

Blade Hardness Gauge versus Snow Density

Pairs of BHG measurements with snow density measurements were taken to test if there is a relation between snow hardness and snow density. A total of 758 in situ pairs were taken in snow profiles consisting of dry snow. The pairs of measurements were broken into corresponding snow grain forms with 354 rounded grain (RG) measurements, 353 faceted grain (FC) measurements, 35 decomposing fragmented grain (DF) measurements and 16 precipitation particle (PP) measurements. Figure 3.10 displays a scatterplot of the density and BHG measurements broken into corresponding snow grain forms. The y-axis is in relation to the snow density measured in kg/m^3 and the x-axis is in relation to the BHG measurements in N of force. Due to the low amount of decomposing fragmented grain and precipitation particle measurements, those two grain forms were grouped together.

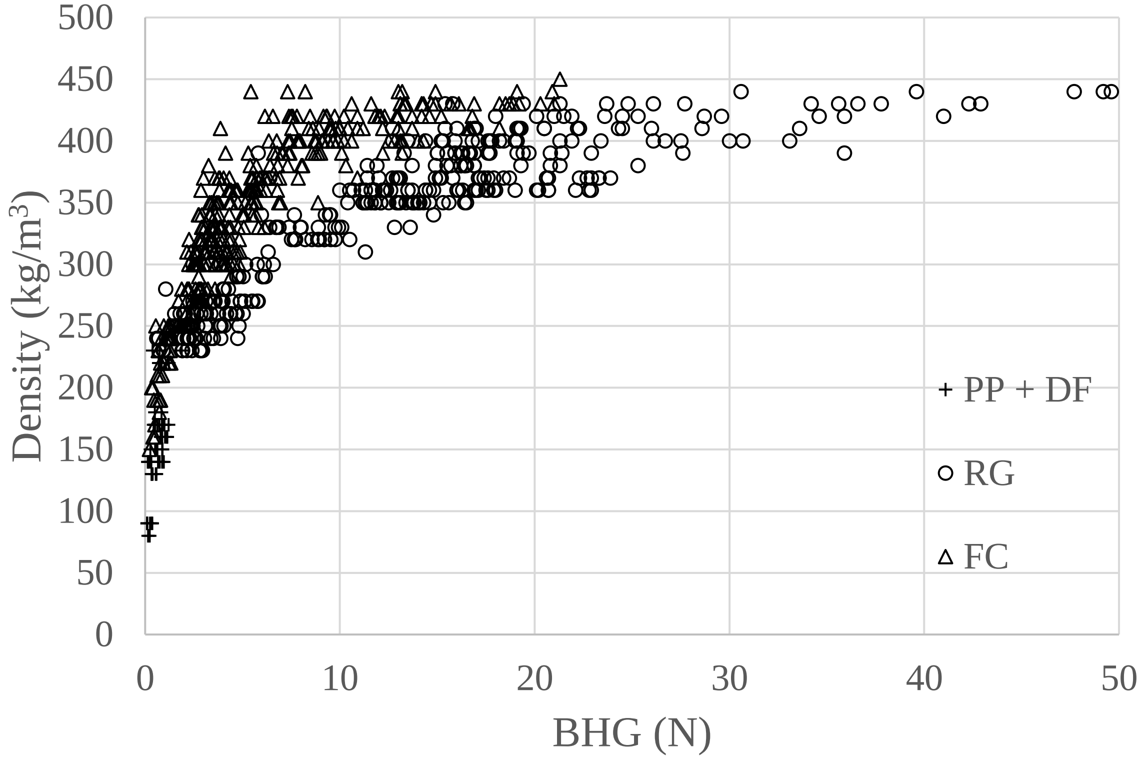

Figure 3.10. Scatterplot comparing snow density to blade hardness gauge (BHG) measurements, n = 758.

For a given snow density there was scatter in the BHG measurements as seen in Figure 3.10. As the density increased the scatter increased in the BHG measurements. The Spearman rank correlation test was utilized for the different grain forms and all grain forms combined. The results of the Spearman rank correlation test with the resulting coefficient, r, are seen in Table 3.1.

Table 3.1. Spearman rank correlation test results for snow density and blade hardness measurements.

Grain Form	Number of Measurements	r	p
RG	354	0.915	< 0.01
FC	353	0.929	< 0.01
PP and DF	51	0.615	< 0.01
Combined	758	0.858	< 0.01

The Spearman rank correlation test resulted in strong positive correlations between density and BHG measurements for all types of snow grains with faceted grains having the strongest correlation.

Multiple studies in the past have found a linear relationship between log hardness and density (Bull, 1956; Keeler & Weeks, 1968; Martinelli, 1971). Figure 3.11 displays a scatterplot of the density and log BHG measurements broken into corresponding snow grain forms. The y-axis is in relation to the snow density measured in kg/m^3 and the x-axis is in relation to log BHG measurements. Due to the low amount of decomposing fragmented grain and precipitation particle measurements, these two grain forms were grouped together.

Linear regression analysis was carried out on the paired density log BHG measurements. The linear regression analysis was utilized for the different grain forms and all grain forms combined. The density was regressed to the BHG measurements using (10).

$$\rho = a + b\ log(B) \qquad (10)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index measured in N, a and b are empirical fitting constants the author used based on the density and BHG measurements. Table 3.2 displays the results of the linear regression analysis along with the empirical constants, a and b, the coefficient of determination, R^2, the significance level, p, and the standard error of regression, S.

Table 3.2. Linear regression analysis for paired snow density and blade hardness measurements.

Grain Form	Number of Measurements	a	b	R^2	p	S
RG	354	196.9	145.8	0.87	< 0.01	22.2
FC	353	231.1	169.3	0.88	< 0.01	22.9
PP and DF	51	179.3	87.6	0.43	< 0.01	31.0
Combined	758	222.5	142.4	0.80	< 0.01	34.7

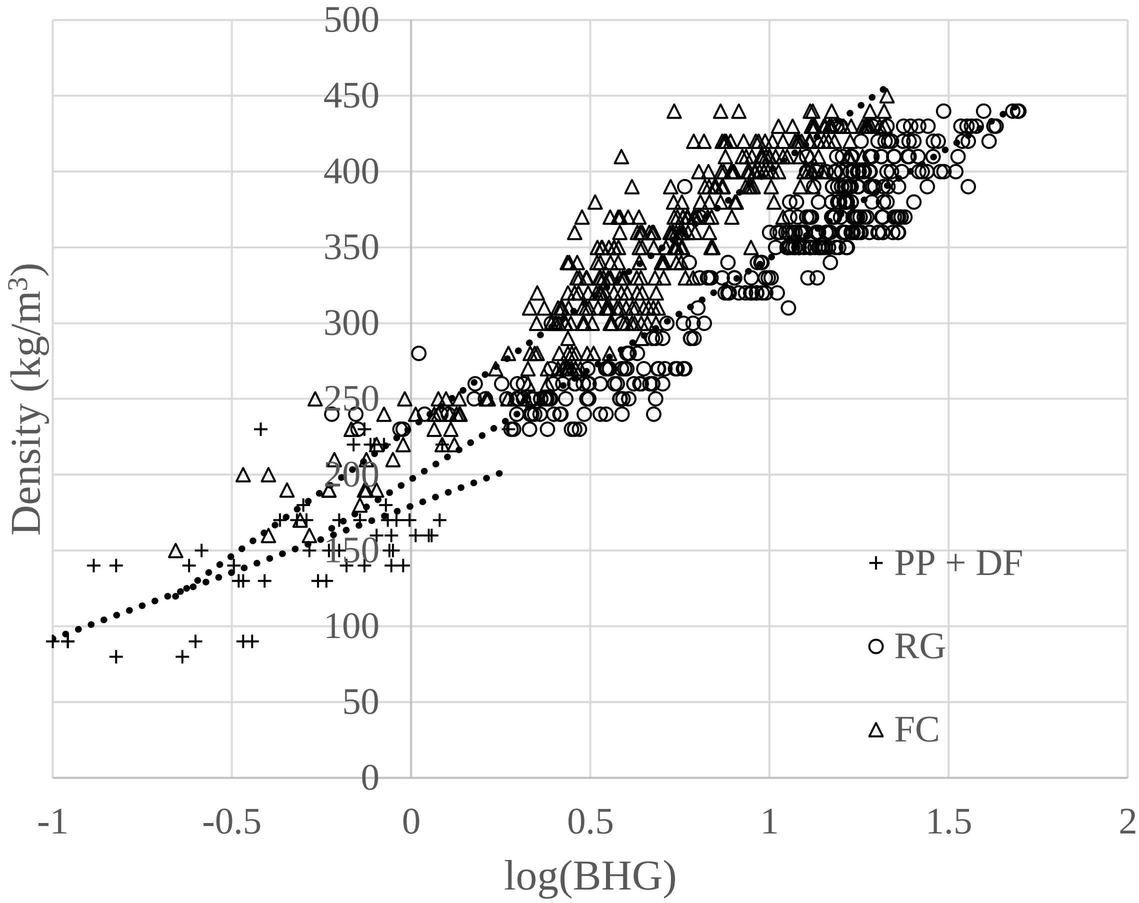

Figure 3.11. Scatterplot comparing snow density to log blade hardness gauge (BHG) measurements, n = 758. The dotted lines represent the linear regressions for each snow grain.

The linear regression analysis results in a reasonable fit for the data. However, it was found that the rounded grains yield a better fit to a non-linear regression of the form:

$$\rho = aB^b \qquad (11)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index (N), a and b are empirical fitting constants the author used based on the density and BHG measurements. Using a non-linear regression of the form in (11) resulted in a better fit (R^2 = 0.88, S = 21.2) and the empirical constants (a = 213.4 and b = 0.199). This relation between snow hardness and density for rounded grains is similar to what was found by Takeuchi et al., Holler & Fromm and Geldsetzer & Jamieson (Geldsetzer & Jamieson, 2000; Höller & Fromm, 2010; Takeuchi et al., 1998). The non-linear regression for rounded grains is seen in Figure 3.12. The y-axis is in relation to the snow density measured in kg/m^3 and the x-axis is in relation to the BHG measurements in N of force.

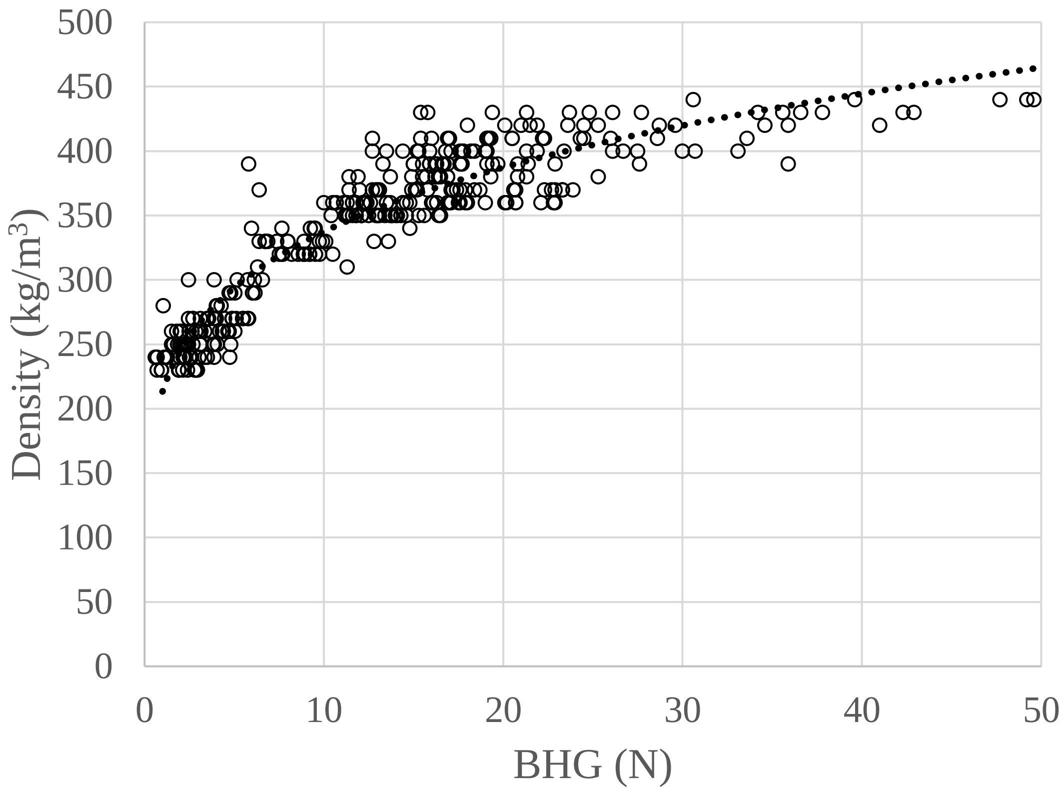

Figure 3.12. Scatterplot comparing rounded grain particle snow density to blade hardness gauge (BHG) measurements, n = 354. The dotted line represents the non-linear regression.

Blade Hardness Gauge versus Hand Hardness Test

Corresponding Hand Hardness Indices with Blade Hardness Gauge Measurements

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 according to the CAA OGRS (Canadian Avalanche Association, 2016b). A total of 4229 BHG measurements were compared with the hand hardness indices. Table 3.3 displays the descriptive statistics of the BHG measurements with the hand hardness indices.

Table 3.3. Descriptive statistics comparing BHG measurements with the hand hardness test from 68 hand hardness profiles by 33 avalanche technicians.

Hand Hardness	Count	Mean (N)	Median (N)	Standard Deviation (N)	Standard Error (N)
F-	25	0.16	0.14	0.14	0.03
F	240	0.28	0.25	0.22	0.01
F+	64	0.36	0.30	0.30	0.04
F (total)	329	0.28	0.24	0.24	0.01
4F-	44	0.53	0.49	0.32	0.05
4F	222	0.65	0.51	0.48	0.03
4F+	79	0.61	0.54	0.31	0.04
4F (total)	345	0.62	0.51	0.43	0.02
1F-	138	1.18	0.91	1.10	0.09
1F	553	2.10	1.33	2.13	0.09
1F+	296	2.93	2.22	2.63	0.15
1F (total)	987	2.22	1.44	2.26	0.07
P-	514	5.21	3.97	4.01	0.18
P	1451	8.05	6.71	5.79	0.15
P+	432	12.45	11.05	8.81	0.42
P (total)	2397	8.23	6.58	6.55	0.13
K-	56	16.38	16.90	6.68	0.89
K	115	23.48	22.30	8.87	0.83
K+	0	~	~	~	~
K (total)	171	21.16	20.10	8.87	0.68

A box plot illustrating the hand hardness indices compared to the BHG measurements is seen in Figure 3.13. The y-axis has the blade hardness values, measured in N of force. The x-axis breaks the box plots up into the different hand hardness indices. The shaded squares represent the interquartile ranges, the line in the shaded squares represents the medians and the whiskers represent the minimum and maximum ranges found in the BHG measurements. Due the linear scale it is difficult to see the overlap of the box plots in the F and 4F indices. A log scale box plot is seen in Figure 3.14 to better visualize the overlap between hand hardness

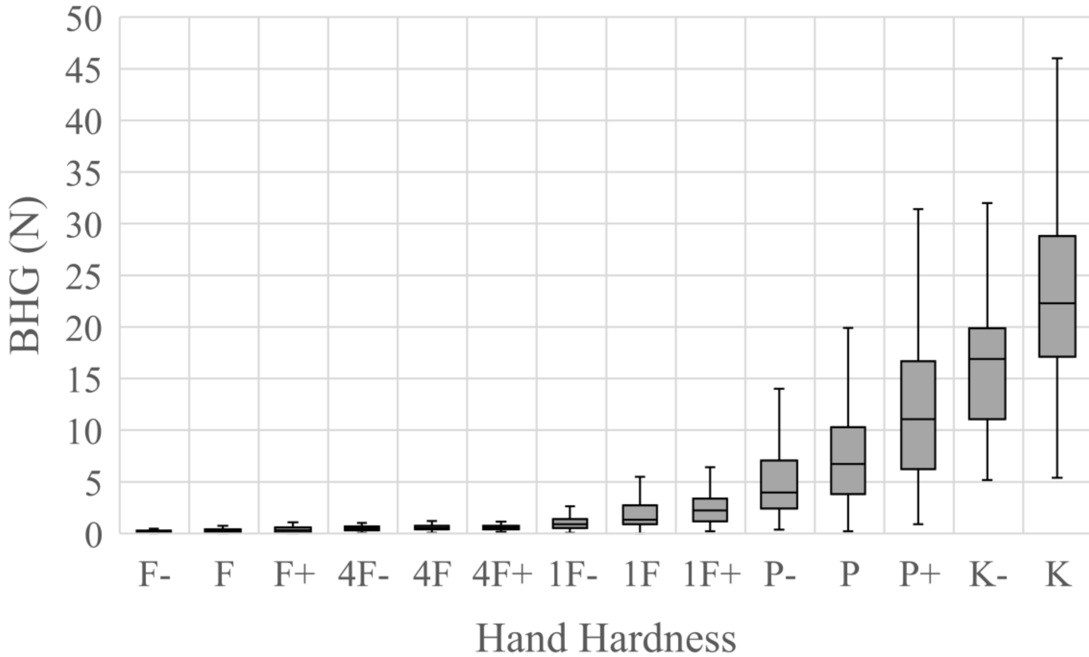

Figure 3.13. Linear box plot comparing hand hardness indices with blade hardness gauge (BHG) measurements from 68 hand hardness profiles by 33 avalanche technicians.

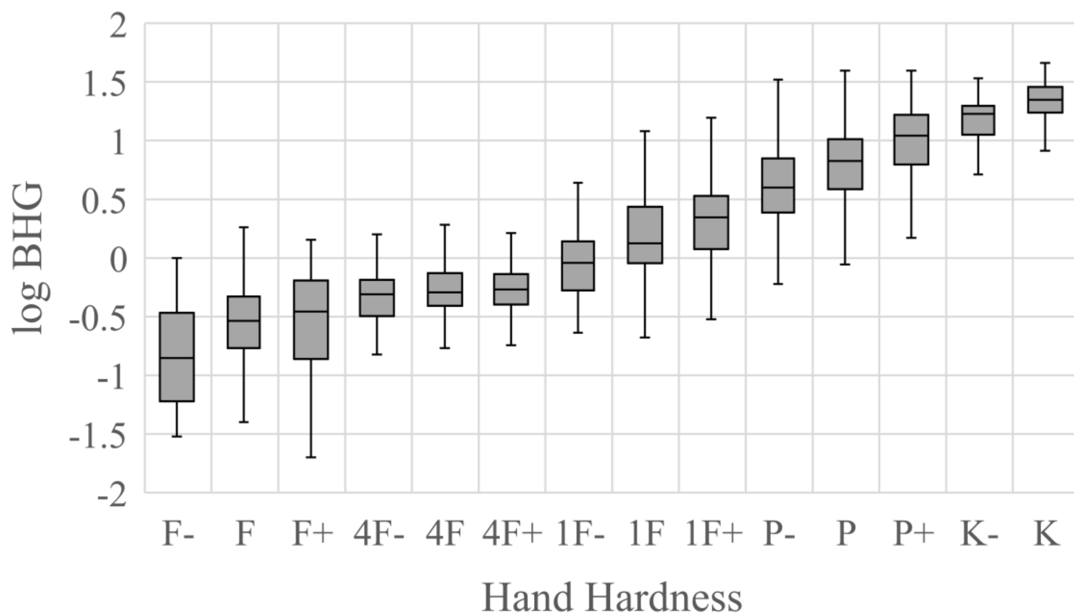

Figure 3.14. Log box plot comparing hand hardness indices with blade hardness gauge (BHG) measurements from 68 hand hardness profiles by 33 avalanche technicians.

indices. The y-axis has the log of the blade hardness values. The x-axis breaks the box plots up into the different hand hardness indices.

The Kolmogorov-Smirnov normality test was used to see if blade hardness measurements were distributed normally with respect to their hand hardness indices. The results of these test are seen in Table 3.4.

Table 3.4. Kolmogorov-Smirnov Normality test results for hand hardness and corresponding blade hardness gauge measurements operators (non-normal distribution if $p \leq 0.05$).

Hand Hardness	KS Normality Test p value
F-	< 0.01
F	< 0.01
F+	0.03
4F-	0.04
4F	< 0.01
4F+	< 0.01
1F-	< 0.01
1F	< 0.01
1F+	< 0.01
P-	< 0.01
P	< 0.01
P+	< 0.01
K-	> 0.15
K	> 0.15

The results show highly skewed data for each hand hardness index. Only the K- and K indices have data that supports a normal distribution. With these results the mean values seen in Table 3.3 are of less value than the median values. The Kruskal-Wallis (K-W) and Mann-Whitney (M-W) tests were used to test to see if there was a statistically significant difference between the hand hardness indices. Table 3.5 displays the results of statistical comparison tests focusing on individual hand hardness indices and the +/- indices.

Table 3.5. Statistical tests comparing the differences of median values with respect to hand hardness indices and corresponding blade hardness gauge measurements (statistically the same if $p \leq 0.05$).

Index Comparison	Statistical Test	p
F-, F, F+, 4F-, 4F, 4F+, 1F-, 1F, 1F+, P-, P, P+, K-, K	K-W	< 0.01
F, 4F, 1F, P, K	K-W	< 0.01
F-, F, F+	K-W	< 0.01
4F-, 4F, 4F+	K-W	0.235
1F-, 1F, 1F+	K-W	< 0.01
P-, P, P+	K-W	< 0.01
F, F+	M-W	0.099
K-, K	M-W	< 0.01
F, 4F	M-W	< 0.01
4F, 1F	M-W	< 0.01
1F, P	M-W	< 0.01
P, K	M-W	< 0.01
F+, 4F-	M-W	< 0.01
4F+, 1F-	M-W	< 0.01
1F+, P-	M-W	< 0.01
P+, K-	M-W	< 0.01

Results show there is no significant difference between the F and F+ indices. As well there is no significant difference between the 4F-, 4F, and 4F+ indices. All other hand hardness indices have statistically significant differences in their median values.

Comparison of CAA Level 1 and Level 2 Operators

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 certificate 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 certificate were taken with corresponding BHG measurements. A box plot graph illustrating the hand hardness indices compared to the BHG measurements is seen in Figure 3.15. The y-axis has the log of the blade hardness values. The x-axis breaks the box plots up into the different hand hardness indices and separates Level 1 and Level 2 operators. The shaded

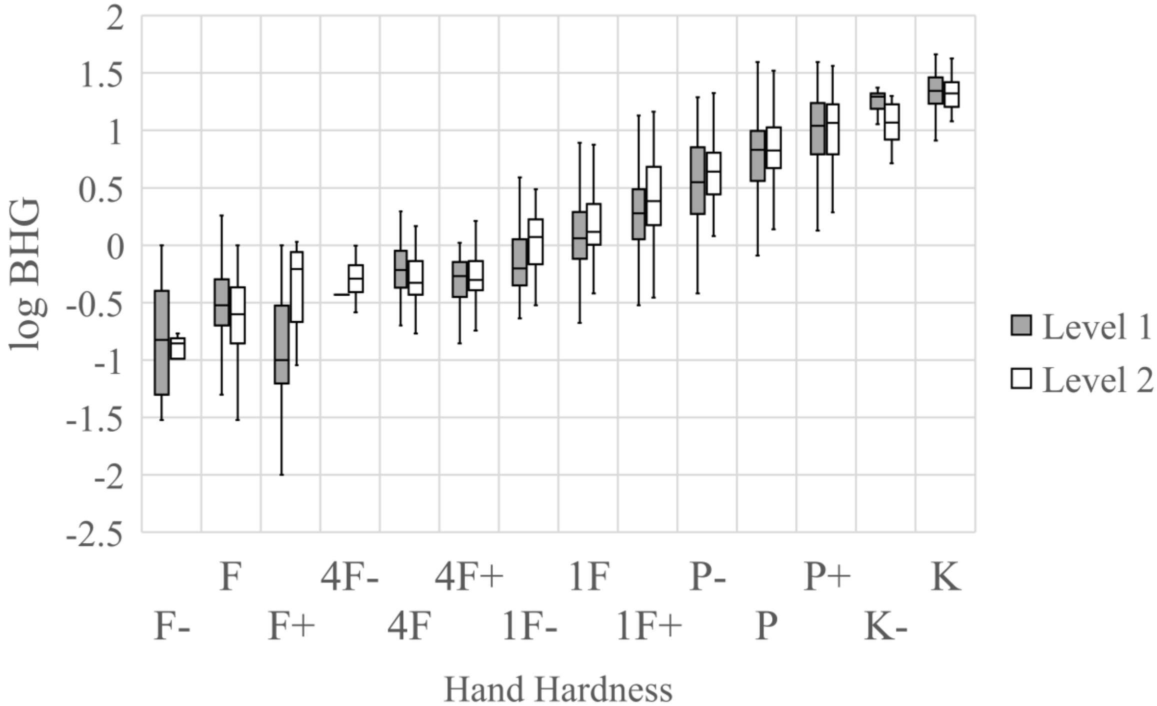

Figure 3.15. Log box plot comparing hand hardness indices with blade hardness gauge (BHG) measurements by CAA Level 1 and Level 2 operators.

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.

Looking at Figure 3.15 it is seen that for all hand hardness indices except F+, 4F-, 1F-, and K- the Level 1 and Level 2 operators have medians in the interquartile range of each other. This illustrates that Level 1 and Level 2 operators have similar hand hardness indices. The M-W test was used to test to see if there was a statistically significant difference between the hand hardness indices of Level 1 and Level 2 operators.

Table 3.6 displays the results of M-W tests comparing Level 1 and Level 2 Operators.

Table 3.6. Mann-Whitney results comparing hand hardness indices and corresponding BHG measurements of CAA Level 1 and Level 2 operators, significance level ($p \leq 0.05$).

Hand Hardness	p
F-	0.849
F	0.874
F+	0.047
4F-	~
4F	0.035
4F+	0.546
1F-	< 0.01
1F	0.019
1F+	0.012
P-	0.018
P	0.092
P+	0.721
K-	< 0.01
K	0.532

Results show there is no significant difference between Level 1 and Level 2 operators in the F-, F, 4F+, P, P+ and K hand hardness indices. With the interquartile ranges and results from the M-W tests the data supports the replication of hand hardness indices between Level 1 and Level 2 operators. Of note, Level 2 operators showed no statistical difference between F+, 4F-, 4F, and 4F+ hand hardness indices (Kruskal-Wallis, $p = 0.277$).

Side by side hardness profiles

To test the reproducibility of the hand hardness test and the BHG, avalanche technicians took corresponding hand hardness and BHG measurements one after another (the subsequent technician did not know the measurements the previous technician measured to maintain independence). These sets of measurements were taken in the same snow profile with minimal time in between technicians, to reduce the effects of weather, and minimal spacing, to reduce the effects of spatial variability in the snowpack. Through the 2020/21 and 2021/22 field seasons 286 snow layers were compared with the hand hardness test and 208 snow layers were

Table 3.7. Side by side snow hardness profiles comparing the reproducibility of the hand hardness test and BHG amongst different avalanche technicians

Layers Compared	Method	Layers in agreement	Percentage of layers in agreement (%)
286	Hand Hardness with ± indices	115	40.2
286	Hand Hardness without ± indices	194	67.8
208	BHG	188	90.4

compared with the BHG. Results of the reproducibility of the hand hardness test and the BHG are seen in Table 3.7.

Table 3.7 shows that the percentage of layers in agreement within current measurement precision between avalanche technicians was 90.4% using the BHG compared to 40.2% using the hand hardness test with the ± indices. This shows that the BHG is superior to the hand hardness test for measuring snow hardness between avalanche technicians. Without the ± indices the reproducibility of the hand hardness test amongst avalanche technicians can greatly improve as the percentage of layers in agreement within current measurement precision rose to 67.8%.

Blade Hardness Gauge versus Extended Column Test

On January 30, 2022, a layer of surface hoar (SH) snow crystals was buried by snow across the northern Purcell Mountains around Golden, B.C. The buried surface hoar became a persistent weak layer. From February 14 to 17, 2022, a total of 24 extended column tests (ECT) were carried out to test the reactivity of the SH layer, measure the hardness of the snowpack and measure the hardness of the SH layer with the BHG. For each ECT carried out (dry snow) the depth and size of SH, angle of slope and ECT propagation results were recorded. The snow hardness was measured with the BHG in roughly 2 cm increments from the top of the snowpack to 30 cm below the SH layer with added measurements roughly 1 cm above and 1 cm below the SH layer. Figure 3.16 shows a picture of the buried SH layer on February 16, 2022, in the northern Purcell Mountains.

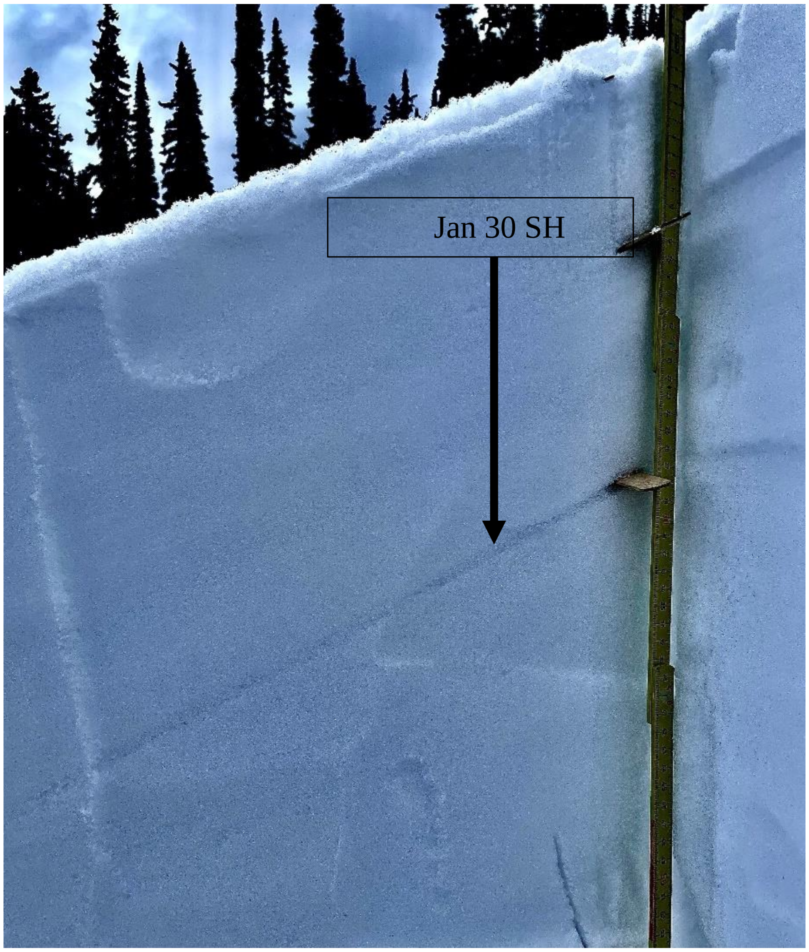

Figure 3.16. Buried January 30 surface hoar layer in the northern Purcell Mountains (photo by author).

Of the 24 ECTs, 13 of the tests resulted in the SH propagating the full 90 cm across the column. Table 3.8 displays the results of the 24 ECTs broken up into propagating < 90 cm and propagating the full 90 cm. To compare the full propagation results with the non full propagation results the means were compared with the two-sample t-test. These results are also seen in Table 3.8. For the Two-sample T-test a significance threshold was set at ($p < 0.05$).

Table 3.8. Results of 24 extended column tests carried out on January 30 surface hoar layer. The p value is from a Two-sample T- test comparing the samples of differing propagation distance.

Propagation Distance (cm)	< 90	90	p
Count	11	13	~
Surface Hoar Grain Size (mm)	1.91 ± 0.24	2.38 ± 0.13	0.119
Depth of Surface Hoar (cm)	24.18 ± 0.89	25.54 ± 0.49	0.222
Surface Hoar Hardness (N)	0.34 ± 0.05	0.29 ± 0.03	0.428
Slope Angle (°)	14.82 ± 2.66	14.69 ± 2.14	0.972
Hardness Difference 1cm Above (N)	0.57 ± 0.08	0.78 ± 0.12	0.171
Hardness difference 1cm Below (N)	0.13 ± 0.05	0.30 ± 0.06	0.061
Mean Slab Hardness (N)	0.46 ± 0.03	0.52 ± 0.04	0.209
Mean Bed Surface (1 to 10 cm below Surface Hoar) Hardness (N)	0.75 ± 0.03	0.89 ± 0.03	0.012

Looking at the results from the two-sample t-tests the only significant statistical difference between the ECT tests propagating the full 90 cm with the ECT tests propagating less than 90 cm is the mean hardness of the bed surface. It is worth noting the other large differences involve the size of the SH grains, the hardness of the SH compared to the hardness of the snow 1 cm above and 1 cm below the SH and the mean slab hardness.

Chapter 4. Techniques and uses for the Blade Hardness Gauge

This chapter discusses techniques and uses for the blade hardness gauge (BHG). The techniques will be in relation to the insertion rate of the BHG into snow, the use of multiple BHGs and the orientation of the BHG into the snow. This chapter discusses ways to estimate snow density with the blade hardness gauge (BHG) as there are variations in density measurements based on the density cutter used, the inability to measure the density of thin layers and to potentially save time in the field. A comparison of the hand hardness test with using the BHG is done to correlate the two snow hardness methods. Comparing the two methods created a blade hardness to hand hardness scale to be utilized for teaching the hand hardness test to new practitioners. The chapter concludes with how blade hardness measurements correspond with extended column tests.

Insertion Rate of the Blade Hardness Gauge

The insertion rate of the BHG is important to consider while using the gauge to measure the hardness of snow. The data supports there is a statistically significant difference between fast (≈ 10 cm/s) and slow (≈ 1-3 cm/s) insertion rates, Wilcoxon signed-rank test ($p < 0.01$), as seen in Figure 3.1. The data also indicated slow insertion rates result in higher data scatter in each snow layer as seen in Figure 3.3. As the gauge is pushed into the snow with a slow insertion rate, it may be the case, that the blade allows compaction of the snow ahead of the blade resulting in the higher and less consistent measurements. Further work on the microscopic effects of the blade would be needed to verify the potential compaction of snow. There is further variability within each measurement, for both the fast and slow insertion rates, as each measurement was taken by the author not a machine.

The original snow resistograph developed by Bradley in 1966 used a thin blade to measure the hardness of snow. The operator of the snow resistograph pushed the blade, attached to a probe, down to the bottom of the snowpack, rotated it 90 degrees and then withdrew the blade upwards with the resistance of the snow being recorded against the thin blade. The varying rate of withdrawing the blades from the snow resulted in varied hardness measurements. If the rate of withdrawal was too slow there was compaction of snow against the blade. Through multiple trials it was found that the withdrawal rate of 10 cm/s was the optimum rate for consistency (Bradley, 1966). The results Bradley found are similar to the results of this study in relation to the BHG.

In 1977, Fukue used a thin blade apparatus to measure the hardness of snow. The apparatus included a thin blade, 12 mm wide and 0.6 mm thick mounted onto a actuator which mechanically inserted the blade into the snow. During the testing it was discovered there was a ductile to brittle transition at a penetration rate of 0.025 cm/s with the snow exhibiting ductile properties below 0.025 cm/s and the brittle properties above 0.025 cm/s. By measuring the hardness of snow above 0.025 cm/s it can be assumed that the thin blade penetration was measuring snow characteristics without the change of the initial properties such as density. Increasing the insertion rate to 0.06 cm/s resulted in consistent thin blade force measurements (Fukue, 1977). Although the current study did not look at the change of ductile to brittle properties by using the fast insertion rate of 10 cm/s it is measuring the snow hardness in the brittle range identified by Fukue.

During the first prototyping of the BHG done by Borstad and McClung, they found no statistically significant difference between fast and slow insertion rates. The fast (≈ 10 cm/s) and slow (1-3 cm/s) were measured subjectively by the operator and done by only one operator to reduce variability. That study used the initial BHG prototype which they concluded had limitations in measuring snow hardness in soft snow, needed a higher a resolution and did not work well in cold temperatures (Borstad & McClung, 2011). The current study used the latest model of the BHG produced by Fraser Instruments Ltd that has more resolution (precise to 0.05 N) and an operating temperature of (-20 to 40°C).

With these results and confirmation with past literature the author recommends using a fast insertion rate of approximately 10 cm/s with the BHG into each snow layer to gain consistent results with the BHG. For the BHG to be used as a standard for measuring snow hardness it is imperative to use techniques that gain consistency in measurements amongst users. Using the fast insertion rate will result in more consistent measurements amongst all users.

Blade Hardness Gauge Variability

The latest iteration of the BHG is being produced by Fraser Instruments Ltd. The gauge utilizes a thin blade that is 0.6 mm thick with a width of 10.0 cm, has a range of 0–50 N and is precise to 0.05 N. If the BHG is to be used as a standard for measuring snow hardness it is imperative gauges produced by the manufacturer are consistent with one another. The author of this thesis acted as a 3rd party to compare the replication of two BHGs. One BHG was provided by the manufacturer, and one was provided by Parks Canada.

Newton's third law of motion states that for every force there is an equal and opposite reaction force. If the gauges are to be consistent with one another then theoretically the gauges should read the same force value when pressed together. The data, seen in Figure 3.4 and Figure 3.5, supports that there is no statistically significant difference between the two gauges when they were pressed together ($N = 250$, linear regression coefficient of determination, $R^2 = 0.99$, and Wilcoxon signed-rank test, $p = 0.414$). This shows that the two gauges are very consistent with another.

The two BHGs were tested for consistency with one another while measuring the blade hardness of snow. Pairs of measurements were taken with each BHG in dry alpine snow of layers of differing snow hardness. The data, seen in Figure 3.6 and Figure 3.7, supports there is no statistically significant difference between the two gauges ($N = 678$, linear regression coefficient of determination, $R^2 = 0.92$, and Wilcoxon signed-rank test, $p = 0.464$) while measuring the hardness of snow. There is greater variability between the two BHGs measuring the blade hardness of snow versus the hardness values recorded being pressed together. This is due to the natural spatial variability of snow. Due to the combination of snow metamorphism, weather patterns and terrain there is constant spatial variability within the snowpack. Although the author minimized the distance (roughly two centimeters) and time between measurements there is no way to completely get rid of spatial variability in a natural snowpack. There is added variability with BHG measurements in the snowpack due to the insertion rate of the BHG. An insertion rate of 10 cm/s was maintained, but that was subjectively judged by the user. Due to both spatial variability and insertion rate variability there is some disagreement between the two gauges while measuring in snow, but they are statistically the same.

Current electronics and manufacturing are able to produce consistency between gauges, so inter-gauge variation should not be a problem. However, as the gauge is used at different temperatures and pressures (altitudes), it would be good practice to perform a standard calibration for the gauge. This could be simply accomplished by hanging a standard mass from the gauge at the start of each run. This would be a simple way to detect technical problems with the BHG. The BHG is reliable, is compact (easy to transport in and around snow study profile plots) and provides consistent measurements with other BHGS.

Orientation of the Blade Hardness Gauge into the snowpack

This study compared using the BHG parallel or perpendicular to the snowpack to measure the snow hardness. In homogenous layers of snow, determined manually by the author, it was found the data supported a statistical difference between using the gauge parallel or perpendicular to the snowpack (Wilcoxon signed-rank test, $p < 0.01$). Across the entirety of the snowpack including homogenous snow layers and distinct snow layers, determined manually by the author, it too found that the data supported a statistical difference between using the gauge parallel or perpendicular to the snowpack (Wilcoxon signed-rank test, $p < 0.01$). For both homogenous layers and across the entirety of the snowpack multiple outliers were found in the dataset illustrating the differences between using the gauge perpendicular versus taking the mean of parallel measurements.

By using the gauge parallel to the snow, the user can find the differences in hardness throughout each snow layer. Snow layers can range from one to hundreds of millimeters in height. Many variables can affect the snowpack and any given snow layer including aspect, wind, temperature, ground roughness, etc. Using the BHG parallel to the snowpack and taking measurements roughly two centimeters vertically apart from one another gives an overall hardness profile of the entire snowpack or the layer in question. For thin persistent weak layers such as layers of buried surface hoar it is only possible to measure the hardness of that weak layer by using the gauge parallel to the snowpack. This is due to the size of the blade. The blade’s 0.6 mm thickness is designed to measure thin persistent weak layers.

To have the BHG become a standard tool for measuring snow hardness it would be best practice to have a standard way of using the tool. From this study, it is recommended using the BHG parallel to the snowpack, taking measurements of the snow top to bottom in two centimeter increments with extra measurements taken at the location of persistent weak layers if they do not line up with the two centimeter increments.

Estimating snow density with the blade hardness gauge

Snow density measurements have been carried out in snow profiles since Walzenbach first documented density profiles in 1930 (Pielmeier & Schneebeli, 2003a). Since then, snow density measurements have become a standard component of a full snow profile (Canadian Avalanche Association, 2016b; McClung & Schaerer, 2006). Various density cutters are used in the avalanche industry, and it has been shown there are significant differences in density measurements (Conger & McClung, 2009). These density cutters come in various sizes with the standards having a volume of 100 or 500 cubic centimeters and a diameter ranging from 3.71 to 5.63 centimeters (Conger & McClung, 2009). Since persistent weak layers can be one millimeter in height it is impractical for density cutters to measure the density of the layers. Density measurements may be used for calculating the total load above a weak layer or finding the water equivalency of the snowpack (Geldsetzer & Jamieson, 2000).

Previous studies have compared snow hardness with snow density such as Bull, Keeler and Weeks and Martinelli who all found there was a linear relationship between the log of snow hardness (measured with the Rammsonde) and density (Bull, 1956; Keeler & Weeks, 1968; Martinelli, 1971). Furthermore, Gold, Kinosita, Takeuchi et al., and Höller & Fromm found a relationship between hardness and density to the fourth power (Gold, 1956; Höller & Fromm, 2010; Kinosita, 1960; Takeuchi et al., 1998). In 2000, Geldsetzer and Jamieson showed one could estimate density with empirical formulas utilizing the hardness and type of snow grain (Geldsetzer & Jamieson, 2000). They found there was a linear relationship between the hand hardness index and the density. The hand hardness indices have surface areas that decrease exponentially as the hand hardness test goes from fist down to knife. With the exponential decrease the linear relationship follows that of a log hardness with density. For rounded grains, Geldsetzer and Jamieson found the relationship of the form of a non-linear regression of a power function (Geldsetzer & Jamieson, 2000). In 2014, Kim and Jamieson tripled the number of layers in the study to reconfirm the relationships between hardness and density with addition of the size of the snow grain. They found that the best way to estimate density from hardness was to use a multivariable regression utilizing grain form, grain size and hand hardness (Kim & Jamieson, 2014).

This study utilized the BHG to measure the hardness of snow to compare with paired snow density measurements. The spearman rank correlation test resulted in strong positive correlations between hardness and density, seen in Table 3.1 and Figure 3.10 ($r = 0.915$, $N = 354$ for rounded grains and $r = 0.929$, $N = 353$ for faceted grains). The correlation between hardness and density was not as strong for precipitation particles and decomposing fragments ($r = 0.615$, $N = 51$) but that may be contributed to lack of measurements. The correlation results show that as the hardness increases the density increases.

To estimate density from hardness, a linear regression analysis was carried out with the data. Faceted grains resulted in a reasonable fit ($R^2 = 0.88$, $S = 22.9$ kg/m^3) using the relationship seen in (12).

$$\rho = 231.1 + 145.8\, logB \qquad (12)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index measured in N, 231.1 kg/m^3 and 145.8 kg/m^3 are empirical fitting constants the author used based on the density and BHG measurements for faceted grains. With the use of blade hardness measurements and (12), an estimate of the corresponding snow density for faceted grains can be found. Geldsetzer and Jamieson reported a standard error of 43 kg/m^3 and a coefficient of determination of 0.51 when utilizing the hand hardness test to estimate the density of faceted grains (Geldsetzer & Jamieson, 2000). Kim and Jamieson reported a standard error of 46 kg/m^3 and a coefficient of determination of 0.53 when utilizing the hand hardness test and grain size to estimate the density of faceted grains (Kim & Jamieson, 2014). The BHG resulted in a significantly lower standard error and a significantly higher coefficient of determination for estimating the density of faceted grains then the use of the hand hardness test.

To estimate density from hardness for rounded grains, a non-linear regression resulted in the best fit for the data ($R^2 = 0.88$, $S = 21.2$ kg/m^3) using the relationship seen in (13).

$$\rho = 213.4B^{0.199} \qquad (13)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index measured in N, 213.4 and 0.199 are empirical fitting constants the author used based on the density and BHG measurements for rounded grains. Blade hardness measurements and (13) can estimate the corresponding snow density for rounded grains. Geldsetzer and Jamieson reported a coefficient of determination of 0.54 (Geldsetzer & Jamieson, 2000) while Kim and Jamieson reported a coefficient of determination of 0.56 when utilizing the hand hardness test to estimate the density of faceted grains (Kim & Jamieson, 2014). The BHG resulted in a significantly higher coefficient of determination for estimating the density of faceted grains then the use of the hand hardness test.

To estimate density from hardness for precipitation particles (PP) and decomposing fragments (DF), a linear regression analysis resulted in the best fit for the data (R^2 = 0.43, S = 31.0 kg/m^3) using the relationship seen in (14).

$$\rho = 179.3 + 87.6\ logB \qquad (14)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index measured in N, 179.3 and 87.6 are empirical fitting constants the author used based on the density and BHG measurements for faceted grains. By using blade hardness measurements and (14), an estimate of the corresponding snow density for precipitation particles and decomposing fragments can be found. Geldsetzer and Jamieson reported a standard error of 27 kg/m^3 (PP) and 30 kg/m^3 (DF), and a coefficient of determination of 0.30 (PP) and 0.52 (DF) when utilizing the hand hardness test to estimate the density of PP and DF grains (Geldsetzer & Jamieson, 2000). Kim and Jamieson reported a standard error of 25 kg/m^3 (PP) and 31 kg/m^3 (DF), and a coefficient of determination of 0.39 (PP) and 0.52 (DF) when utilizing the hand hardness test and grain size to estimate the density of PP and DF grains (Kim & Jamieson, 2014). The BHG resulted in a similar standard error and coefficient of determination for estimating the density of PP and DF grains with the use of the hand hardness test. The author theorizes that with more paired measurements of blade hardness and density would result in better fitting linear relationships with a lower standard error between the log hardness and density of PP and DF grains.

The BHG gives the avalanche technician a tool to measure the hardness of snow and to estimate the density of the snow. With current density samplers it is not always possible to measure the density due to the layer being too thin for the sampler. With the utilization of a thin blade, the BHG can take measurements in these thin layers and then one could use an empirical relationship such as (12, 13 and 14) to estimate the density. Due to the low number of measurements in low density snow (< 220 kg/m^3) further research is needed for more accurate empirical relationships for low density snow. It would be beneficial to continue this research to gain a greater data set of more paired blade hardness and density measurements. The empirical relationships will gain accuracy by introducing more grain forms, sub grain forms and grain sizes. By having these empirical relationships, the total load above a weak layer or the water equivalency of the snowpack may be estimated with blade hardness measurements when it is not possible or practical to take density measurements.

Calibrating the Hand Hardness Test with the Blade Hardness Gauge

The hand hardness test is the standard technique for measuring snow hardness in a profile carried out by avalanche technicians in Canada. The test, introduced by de Quervain in 1950, has the operator exert 10-15 N of force using physical objects of decreasing surface area (fist, four fingers, one finger, pencil and knife) into the snowpack (de Quervain, 1950). The Canadian Avalanche Association has operators add ± indicators to illustrate variations in hardness (Canadian Avalanche Association, 2016b). Unfortunately, the hand hardness test is a subjective test as it relies on a human knowing how much force to put into the snowpack, varying sizes of hand and can be compromised by user bias due to amount of experience (Pielmeier & Schneebeli, 2003b; Pogue et al., 2018).

The initial BHG was designed to measure snow hardness in a quantitative manner and eliminate user bias (Borstad & McClung, 2011). Further research has shown the feasibility of the BHG including using the gauge to measure the hardness of thin weak layers over time (Pogue & McClung, 2016). A study carried out in Glacier National Park was done to correlate the hand hardness test with the BHG. The study compared BHG and hand hardness measurements in 27 snow profiles by 8 different operators and found that the ± indexes used have no meaning, that fist and four fingers hardness is basically the same and that further testing is needed for operator hand hardness bias (Pogue et al., 2018).

The research in this paper set out to further correlate hand hardness measurements with blade hardness measurements and test the replication amongst users of both the hand hardness test and the BHG. Throughout the two-winter field seasons a total of 68 hand hardness profiles by 33 different avalanche technicians were taken with corresponding BHG measurements. Furthermore, 286 snow layers were compared with the hand hardness test and 208 snow layers were compared with the BHG amongst multiple avalanche technicians to test replication of the two methods.

The data from the 68 hand hardness profiles with correlating blade hard measurements, seen in Figure 3.13 and Figure 3.14, resulted in no difference between the ± indices in the four fingers category. Looking at the data from the 19 hand hardness profiles from CAA Level 2 Operators, seen in Figure 3.15, 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). The results do show that there was a statistical difference between the F and 4F categories and in the harder snow categories (1F, P and K) there were significant differences between the ± indices. Although there was significant difference in the ± indices for 1F, P and K there was a lot of overlap amongst avalanche technicians.

The data comparing the replication of the hand hardness test and BHG amongst users resulted in a percentage of layers in agreement for each method. Only 40.2% of layers matched hand hardness indices when including the ± indices in the hand hardness test. This increased to 67.8% of layers matching when the ± indices were removed. Meanwhile the percentage of layers in agreement within current measurement precision reached 90.4% when avalanche technicians were using the BHG.

The results of this research indicate that if the ± indices were removed from the hand hardness test there would be greater reproducibility amongst avalanche technicians. However, on a given day in each snow profile by one avalanche technician, that one avalanche technician can use the ± indices to provide hardness differences between layers. Those ± indices will overlap the other indices over time and will not necessarily be reproduced by another technician. This is due to the inherit flaws of the hand hardness test. The hand hardness test is subjective and can vary amongst avalanche technicians due to hand/glove size and inconsistently applying 10-15 N of force. To accurately measure the hardness of snow of a given layer over time it is recommended to use the BHG instead of the hand hardness test. The hand hardness test is not consistent over time with the results changing day to day, profile to profile.

In contrast, this study and previous studies have shown the BHG is consistent amongst users and can accurately measure snow hardness over time. For avalanche operations that monitor the snowpack over time (e.g. weekly snow profiles) it is recommended that a BHG is used for measuring the snow hardness. This way the operation will be able to track and see the changes in the hardness of specific layer throughout the season or given period.

Although the research illustrates the superiority of the BHG over the hand hardness test with respect to accurately measuring snow hardness, the author predicts that the hand hardness test will continue to be practiced in the avalanche industry. This is due to the hand hardness test being around since 1950 and has been set as an International and Canadian standard for measuring hardness. The hand hardness test also has the benefit of not needing a specialized tool making it accessible and affordable. However, there is needed instruction and training for current and future avalanche technicians to effectively use the hand hardness test.

The BHG is poised to be used as a teaching tool to effectively calibrate new and experienced avalanche technicians to the hand hardness test. With the BHG being a force gauge an avalanche technician can get the feeling of what 10-15 N of force feels like by pressing their hand, finger, or pencil into the gauge itself while being held by another individual. The standard force for the hand hardness test is 10-15 N but many individuals do not know how much force that feels like. By testing oneself with the BHG, one can know how much force is needed to effectively replicate the hand hardness test.

A blade hardness to hand hardness scale is provided in Table 4.1. This scale was produced from the results of this study. To use this scale, in Canada, the author suggests following the guidelines of a test or full snow profile with respect to determining the location of snow layer boundaries set out by the Canadian Avalanche Association (Canadian Avalanche Association, 2016b). Once the snow layer boundaries are in place one can take three consecutive measurements with the BHG in a specific layer. Take the average value of those three measurements with the BHG and compare the average value to the scale seen in **Error! Reference source not found.**. With the scale one can then say this layer is in relation to the specific hand hardness index. The ± indices were not included in the scale as the research illustrates that the ± are not

Table 4.1. 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

consistently replicated amongst users and have significant overlap. The results from Pogue et al (2018) correspond with the hand hardness to blade hardness scale, as the median blade hardness values found in their study are all within the ranges given.

Using the BHG with the accompanying blade hardness and hand hardness scale the gauge can be used as a teaching tool. When first introducing the hand hardness test to new avalanche technicians would give them firsthand knowledge of the force needed and an idea of what the snow feels like. This scale can also be used for experienced avalanche technicians to get them to be more consistent with their peers and colleagues.

The BHG is a reliable and consistent tool for measuring snow hardness. As the hand hardness test is the main standard for measuring snow hardness it was imperative to correlate the blade hardness measurements with the hand hardness indices. This research found that the ± indices are not useful for comparing snow hardness across multiple individuals and across time. The ± are useful to illustrate variations in hardness for a specific profile on a given day. However, the BHG is superior to illustrate the variations in hardness and is more consistent amongst users. The BHG should be utilized for measuring snow hardness over time and as a teaching tool to improve consistency of the hand hardness test.

Blade Hardness in Correspondence with Extended Column Tests

The Extended Column Test (ECT) was developed in 2006 to assess the propagation potential of a snowpack (Simenhois & Birkeland, 2006). The test is now a standard snow instability test used to assess the fracture initiation and propagation of buried weak layers used by professionals and back country recreationalists. This study aimed to find a relationship between blade hardness measurements of the slab, weak layer, and bed surface and ECT propagation results.

A previous study found that the propagation propensity demonstrated by the ECT increased as the hardness of the slab increased (Ross & Jamieson, 2008). In 2007, a study looked at snowpack properties in relation to skier triggered dry snow slab avalanches and found skier triggered avalanches decreased with the increase of weak layer hand hardness. The study also found an increase in skier triggered avalanches as the difference in hand hardness between the weak layer and the adjacent layers (above and below) increased and as the grain size of the weak layer increased (van Herwijnen & Jamieson, 2007).

This study carried out 24 ECTs on the January 30, 2022 surface layer in the northern Purcells near Golden, B.C between February 14 to 17, 2022. 13 of the ECTs propagated the full 90 cm of the isolated column and 11 of the ECTs propagated less than 90 cm. The data, seen in Table 3.8, show there is a statistical difference between the mean hardness of the bed surface in the 10 cm below the surface hoar layer ($p = 0.012$). All other components analyzed are not statistically significant, but the values reinforce findings from previous studies. As the slab hardness increased the frequency of the ECT propagating the full 90 cm increased. As the hardness of the surface hoar decreased the frequency of the ECT propagating the full 90 cm increased. As the difference in hardness between the weak layer and the adjacent layers increased the frequency of the ECT propagating the full 90 cm increased. As the grain size of the weak layer increased the frequency of the ECT propagating the full 90 cm increased. Due to the low number of ECTs and the non-significant findings, more research needs to be carried out to confirm these results.

Chapter 5. Conclusions

By measuring the snow hardness, one gains knowledge with respect to how well the snow grains are bonding, bending, rupturing, and compacting with one another. This is important as the bonding of snow grains (not density) is the critical factor in determining how snow responds to applied loads and stresses (Shapiro et al., 1997). The International and Canadian standards utilize the hand hardness test for measuring snow hardness (Canadian Avalanche Association, 2016b; Fierz et al., 2009). The hand hardness test, while useful, does not provide precise quantitative snow hardness measurements to the avalanche industry. The blade hardness gauge (BHG) is a promising technology that provides avalanche technicians a way to quantitatively measure snow hardness without the known biases of the hand hardness test. This study researched the reliability and integrity of the BHG with respect to measuring snow hardness. This chapter highlights the conclusions of this research with respect to measurement techniques, uses for the BHG, provides suggestions for improvements to be made to the BHG and future research that can be carried out with the BHG.

The insertion rate of the BHG into the snowpack is an important technique for gaining consistency with the gauge amongst users. This study explored the insertion rate with fast (≈ 10 cm/s) and slow (≈ 1-3 cm/s) insertion rates. It was found that there was a statistical difference between the fast and slow insertion rates, Wilcoxon signed-rank test ($p < 0.01$), with the fast insertion rate resulting in less scatter in the data. Comparing theses results with previous literature it is recommended to use an insertion rate of approximately 10 cm/s into the snowpack to gain consistency with the gauge and amongst users. Users of the BHG must be taught to use a consistent fast insertion rate. As users will have to subjectively judge the fast insertion rate there will be variability amongst users. This however is minimal as the results of this study verified that the BHG is more consistent amongst users than the hand hardness test.

Currently the BHG is being produced by Fraser Instruments Ltd. The gauge is a compact unit that withstands cold temperatures and is easy to use in the natural snow environment. This study tested two different BHGs to see if they reliably reported the same hardness with one another and in the natural snowpack. The data supports there is no statistical difference between the two gauges with respect to blade hardness measurements. This supports that the BHG is a reliable device with the ability to compare blade hardness measurements across devices.

The BHG is a force gauge with a range of 0 – 50 N and is precise to 0.05 N. It can reliably measure the hardness of very soft freshly fallen snow up to hard melt-freeze crust layers. 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 author recommends inserting 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.

Blade hardness measurements show a strong positive correlation with paired snow density measurements is dry alpine snow. The blade hardness measurements can then be used to estimate the density of snow with the use of empirical relationships. These estimations gain accuracy by considering the snow grain form that is being measured. For rounded grains the density is estimated by using a non-linear regression of the form:

$$\rho = aB^b \qquad (15)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index measured in N, a and b are empirical fitting constants the author used based on the density and BHG measurements for rounded grains. For all other snow grain forms the density is estimated by using a linear regression of the form:

$$\rho = a + b\ logB \qquad (16)$$

Where ρ is measured in kg/m^3, B is the BHG hardness index measured in N, a and b are empirical fitting constants the author used based on the density and BHG measurements. The empirical relationships between blade hardness and density might be expected to gain precision (lower standard error) with a greater database of paired measurements with respect to low density snow (< 200 kg/m^3), snow grain sizes and snow grain sub forms. If greater precision can be achieved, this may give practitioners another tool to estimate density. Knowing the density accurately gives avalanche practitioners the ability to estimate the applied load above a persistent weak layer and calculate the snow water equivalency of the snowpack. With the 0.6 mm blade the BHG can estimate the density of layers that are too thin for current snow density samplers. Thus, the BHG gives the avalanche technician a tool to measure the hardness and estimate the density of snow.

As the hand hardness test is the current standard for measuring snow hardness in Canada, this study set out to further correlate the BHG with the hand hardness test. The results seen in Table 3.7 show 90.4 % of layers agree within current measurement precision with the BHG while only 40.2 % of layers agree within current measurement precision with the hand hardness test amongst avalanche technicians. Therefore, the BHG is more consistent amongst users than the hand hardness test. The study recommends using the BHG to measure the hardness of snow over time as the hand hardness indices show considerable overlap, especially with the use of ± indices and in soft snow (hand hardness indices Fist and Four Fingers).

The BHG can be used as a teaching tool to introduce and improve consistency of the hand hardness test amongst users. The BHG can be used to show the user what 10-15 N of force feels like, which is the insertion force of the hand hardness test. The BHG can measure the hardness of the snow and then using the provided blade hardness to hand hardness scale seen in Table 4.1, the user can determine which hand hardness index the snow layer is part of. For measuring snow hardness and calibrating the hand hardness test it is recommended to use the BHG. Continuous calibration of the hand hardness test with the BHG could lead to greater consistency amongst avalanche technicians.

The BHG shows promise as a research tool for the continued and future analysis of snow instability tests such as the extended column test (ECT). This study compared the results of 24 ECTs on a layer of buried surface hoar with corresponding blade hardness measurements. The results showed there was greater frequency of propagation of the surface hoar layer as the hardness of the bed surface increased, the hardness of the surface hoar decreased, the slab hardness increased and as the difference between the hardness of the surface hoar layer with the adjacent layers increased. Further tests are needed to replicate this data on more buried persistent weak layers.

Limitations to this research include the types of snow in the natural snowpack. There is inherit variability in the snowpack due to elevation, terrain, and weather. The use of a temperature-controlled snow/cold lab could remedy some of the variability. This research was carried out during the 2020/21 and 2021/22 winter seasons primarily around Golden, British Columbia in the Purcell Mountain Range. All blade hardness measurements were taken in dry snow. Future research with the BHG should also include wet snow measurements. The lack of persistent weak layers throughout the two winter seasons resulted in the inability to gain more data comparing the BHG with ECT results. More measurements with respect to all components would be useful to the results but only so many can be taken in each field season.

The research shows the BHG to be a reliable tool, compact to travel with, easy to use and produces consistent measurements when measuring snow hardness. The main issue with the BHG is data collection with the gauge. Currently there is no way to store data on the gauge or see it real time using a phone/web-based application. While operating the gauge the operator takes the measurement of snow hardness and then must write it down or tell a fellow technician to write it down. Snow observations take place outside in the snow. On any given day the temperature can be well below zero degrees Celsius, there can be wind and/or have precipitation falling. Writing data down in field books in this outdoor environment can be cumbersome and can lead to mistakes.

It is suggested that the manufacturer of the BHGs make the gauge have an internal database where the user can set specific heights in relation to the snowpack (height of snow, height of increments for measurements and height of persistent weak layers). Or have the manufacturer create a phone/web-based app that the BHG is connected to so the operator can create a real time hardness profile of the snowpack. Many avalanche technicians around the world create computer generated snow profiles on the website snowpilot.org. SnowPilot follows the Canadian Observational Guidelines and Recording Standards. If the potential internal database or application could link the BHG data to an existing snow profile software, there would be many more avalanche technicians willing to use the BHG. With the use of an app and the widespread mobile broadband network these snow hardness profiles could be uploaded to the appropriate institution instantaneously. The author has no suggestions for improving the actual gauge with respect to precision and measuring capabilities. By improving the way, the operator collects and visualizes the data would make it even more user friendly and help aid data collection for future research.

The current research shows that the BHG is a reliable and consistent for measuring snow hardness. These qualities make the BHG a great tool to be used in future research. This study illustrated that the BHG can be utilized to estimate snow density. A greater data base is needed to improve the empirical relations used to estimate the density. More measurements with all types of snow grains, subcategories of snow grains and snow grain size is needed to improve the empirical relations. This study focused on dry alpine snow, future studies may also look at the comparison of snow density and blade hardness in wet snow.

The BHG may be able to predict the results of extended column tests (ECT) and other snow instability tests such as the propagation saw test. This study did not have enough data to produce concrete evidence that the BHG could predict the results of an ECT. The BHG provides a tool to measure the hardness of the snowpack above, below and of the weak layer itself. There may be a relationship between those values and the results of such instability tests. Future research with the BHG will lead the way for improving safety for avalanche-affected transportation corridors, infrastructure, ski resorts and the general public.

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Appendix

Table A.1. Descriptive statistics comparing blade hardness gauge measurements with the hand hardness test for CAA Level 1 Operators.

Hand Hardness	Count	Mean (N)	Median (N)	Standard Deviation (N)	Standard Error (N)
F-	19	0.17	0.11	0.16	0.04
F	133	0.29	0.25	0.25	0.02
F+	16	0.17	0.10	0.20	0.05
F (total)	168	0.27	0.23	0.24	0.02
4F-	1	0.37	0.37	0.00	0.00
4F	94	0.75	0.61	0.55	0.06
4F+	32	0.55	0.54	0.23	0.04
4F (total)	127	0.69	0.59	0.49	0.04
1F-	64	0.90	0.63	0.74	0.09
1F	259	1.78	1.15	2.31	0.14
1F+	167	2.71	1.90	2.75	0.21
1F (total)	490	1.98	1.23	2.41	0.11
P-	264	4.95	3.55	4.00	0.25
P	873	7.88	6.76	5.72	0.19
P+	304	12.73	10.95	9.75	0.56
P (total)	1441	8.37	6.82	7.01	0.18
K-	14	18.49	19.70	3.63	0.97
K	73	23.49	22.10	9.42	1.10
K+	0	~	~	~	~
K (total)	87	22.68	21.60	8.94	0.96

Table A.2. Descriptive statistics comparing blade hardness gauge measurements with the hand hardness test for CAA Level 2 Operators.

Hand Hardness	Count	Mean (N)	Median (N)	Standard Deviation (N)	Standard Error (N)
F-	6	0.13	0.14	0.04	0.02
F	55	0.28	0.25	0.19	0.03
F+	18	0.41	0.42	0.32	0.08
F (total)	79	0.30	0.24	0.23	0.03
4F-	32	0.54	0.51	0.21	0.04
4F	51	0.55	0.47	0.27	0.04
4F+	33	0.65	0.50	0.39	0.07
4F (total)	116	0.57	0.49	0.30	0.03
1F-	45	1.48	1.18	1.48	0.22
1F	131	1.76	1.31	1.26	0.11
1F+	87	3.37	2.43	2.74	0.29
1F (total)	263	2.24	1.50	2.07	0.13
P-	123	5.66	4.37	4.61	0.42
P	385	8.46	6.67	5.97	0.30
P+	110	12.42	11.65	7.26	0.69
P (total)	618	8.61	6.52	6.34	0.25
K-	25	12.13	11.70	4.47	0.89
K	30	22.51	21.00	7.83	1.43
K+	0	~	~	~	~
K (total)	55	17.79	17.00	8.32	1.12

Table A.3. Kolmogorov-Smirnov Normality test results for hand hardness and corresponding blade hardness gauge measurements separated by CAA Level 1 and Level 2 operators (Non-normal distribution if $p \leq 0.05$).

Hand Hardness	Level 1 p	Level 2 p
F-	0.037	0.047
F	< 0.010	0.144
F+	< 0.010	> 0.100
4F-	~	> 0.150
4F	< 0.010	< 0.010
4F+	> 0.150	< 0.010
1F-	< 0.010	< 0.010
1F	< 0.010	< 0.010
1F+	< 0.010	< 0.010
P-	< 0.010	< 0.010
P	< 0.010	< 0.010
P+	< 0.010	> 0.150
K-	> 0.100	> 0.100
K	> 0.150	> 0.150

Table A.4. Descriptive statistics for trials of ten fast versus ten slow insertion rate measurements.

Trial	1		2		3		4		5		6		7		8		9		10		11	
Insertion Rate	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
Mean (N)	0.51	0.85	0.55	0.67	1.64	1.65	1.67	1.95	3.69	4.31	4.46	6.62	4.49	5.66	5.78	8.21	6.05	7.84	10.65	13.81	19.42	25.75
Median (N)	0.51	0.87	0.55	0.67	1.58	1.65	1.64	1.85	3.63	4.11	4.37	7.04	4.48	5.66	5.80	7.62	5.92	7.85	10.65	13.30	19.45	23.45
Standard Deviation (N)	0.04	0.19	0.06	0.07	0.14	0.13	0.14	0.33	0.20	0.98	0.26	1.72	0.21	1.36	0.15	1.96	0.39	0.78	0.32	3.32	0.69	5.43
Standard Error (N)	0.01	0.06	0.02	0.02	0.04	0.04	0.05	0.10	0.06	0.31	0.08	0.55	0.07	0.43	0.05	0.62	0.12	0.25	0.10	1.05	0.22	1.72
Coefficient of Variation %	8.36	22.28	10.57	10.99	8.35	8.09	8.56	16.95	5.50	22.71	5.90	26.06	4.68	23.97	2.58	23.94	6.51	9.90	3.01	24.06	3.54	21.08