

# THE EFFECTS OF EXPLOSIVES ON THE PHYSICAL PROPERTIES OF SNOW

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**ABSTRACT:** Explosives are a critically important component of avalanche control programs. They are used both to initiate avalanches and to test snowpack instability by ski areas, highway departments and other avalanche programs around the world. Current understanding of the effects of explosives on snow is mainly limited to shock wave behavior exhibited through stress wave velocities, pressures and attenuation. This study aims to enhance current knowledge of how explosives physically alter snow by providing practical, field-based observations and analyses that quantify the effect of explosives on snow density and snow stability test results. Density and stability test results were evaluated both before and after the application of 0.9 kg cast pentolite boosters as air blasts. Changes in these properties were evaluated at specified distances up to 4 meters (m) from the blast center using a density gauge and Compression Tests (CTs). Statistically significant density increases occurred out to a distance of 1.5 m from the blast center and down to a depth of 60 centimeters (cm). Statistically significant density increases were also observed at the surface (down to 20 cm) out to a distance of 4 m. Results from CTs showed a decrease in the number of taps needed for column failure in the post explosive tests. The results of this study provide a better understanding of the physical changes in snow following explosives, which may lead to more effective and efficient avalanche risk mitigation.

## 1. INTRODUCTION

Explosives are a critically important component of avalanche risk mitigation programs. They are used by ski areas, highway departments and other avalanche programs to both initiate avalanches and to test snowpack stability. Despite their importance, knowledge about the effects of explosives on the physical properties of snow is limited. This research provides experimental, field-based observations and analyses of the changes in snow density and snow stability test results after the application of explosives, thereby contributing to the understanding of how explosives affect the physical properties of snow.

While knowledge of the physical effects of explosives on snow is limited, many prior studies have examined shock wave propagation through the snowpack, focusing on stress wave velocities, pressures and attenuation (e.g. Livingston, 1968; Lyakhov et al., 1989; Mellor, 1973; Wisotski and Snyer, 1966). Gubler (1977) examined stress wave attenuation as a result of charge size, placement, type of explosive, snow type and ground type; he determined that the most

effective charge placement was one to two meters above the snow surface. Ueland (1992) investigated the effectiveness of different charge types and sizes in various snowpacks. His findings confirmed the effectiveness of air blasts suspended above the snow surface and determined that snow hardness influences shock wave attenuation more than density. Snow, unlike other materials that are routinely tested with explosives such as soil or rock, exhibits rapid attenuation of shock waves (Mellor, 1968; Wisotski and Snyer, 1966; Livingston, 1968). In experiments involving above-snow explosive blasts, mach-region peak pressures were found to be lower over snow than over bare ground or concrete indicating much higher shock wave attenuation rates in snow (Wisotski and Snyer, 1966). This rapid attenuation is a unique response that sets snow apart from those other materials.

When explosives are in direct contact with snow, the normal explosive reaction is impeded. Wisotski and Snyer (1966) suggested that this is a result of the unique structure and composition of snow. Snow is a composite material made up of air, ice and/or water. Pore space between the solid components makes up 40-97% of total snow volume (McClung and Schaerer, 2006), a much larger percentage than in most other materials. For example, the porosity of rock is 1-40% and

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that of concrete is 1-10% (WGNHS, 2011; Lamond, 2006).

Modeling by Brown (1981) predicted that snow density would increase in the immediate area surrounding a blast, but the author did not provide data to support this prediction. Frigo et al. (2010) detonated dynamite and emulsion charges above, on and below the snow surface and made snowpack measurements including snow density, but changes were only documented at the blast crater and the results were inconclusive. Miller et al. (2011) presented a model predicting some of the responses of snow to an explosive blast. The model evaluated pressure and stress waves from both surface and air blasts of 0.9 kg and 1.8 kg pentolite charges. It also evaluated density changes and predicted increasing density in the region below the explosive (Miller et al., 2011). Miller et al. (2011) theorized that the region affected by a stress wave might provide a gauge of the effectiveness of explosives in avalanche control work. These studies provide insight into the behavior of shock waves in snow, but there is still a significant lack of information and observational data on the physical changes in snow that occur as a result of using explosives.

The goal of this paper is to quantify pre- and post-explosives use changes in snow density and snow stability test results, and the distances over which those changes can be measured. The following research questions will be addressed:

- 1) After the application of explosives, is there a change in snow density and to what distances and depths can that change be measured in the field?
- 2) After the application of explosives, is there a change in snow stability test results, and at what distances can that change be quantified?

To address these goals, snow density was measured before and after applying explosives (as air blasts) at four distances from the blast center and down to a depth of 1 meter (m). Compression Tests (CTs) (Greene et al., 2010) were conducted before and after air blast detonation at two distances from center for each detonation.

Repeated measurements of the changes in snow density and snow stability test results following detonation of explosives have not previously been made. This study provides observational data and analyses to help bridge this gap between technical knowledge and practical field-based knowledge on

how snow responds to explosives. This research provides quantifiable information about how select snow properties change under the influence of explosives, which may lead to improvements in avalanche control operations.

## 2. METHODS

### 2.1 *Study Site*

Two sites in southwestern Montana, one at Moonlight Basin Ski Resort and one at Bridger Bowl Ski Area, were used for data collection. Both study sites lie in closed areas inside the ski area boundaries. The sites are located in meadows under open forest canopies; both meadows have slope angles ranging from 7° to 20°. These areas were free from skier traffic and avalanche mitigation. Low-angle slopes were chosen for this study in order to prevent snow loss from avalanching during the tests and to minimize avalanche risk during data collection.

### 2.2 *Field Methods*

Twenty-five tests of air blast explosions were conducted at Moonlight Basin and two were conducted at Bridger Bowl. A blast center location was chosen and marked with bamboo. At each test site, four snowpit locations were measured at specified distances from the blast center and marked without disturbing snow between the blast center and the pit locations. Snowpits in all tests were placed at distances of 0.5, 1, 1.5 and 4 m from the blast center. To ensure that the post-blast measurements would be taken exactly at these marked locations in undisturbed snow, pre-blast snowpits were located approximately 0.5 m downhill of the marked locations (Figure 1). Although one representative pre-blast pit for each detonation would have been sufficient for baseline measurements, a pre-blast pit was dug for each distance. This was done to minimize the effects of spatial variability. The snowpits were dug to a depth of 1 m where the snow cover exceeded 1 m and to the ground where snow height was less than 1 m. These distances are based on the model by Miller et al. (2011), which predicts that the compaction zone from a 1.8 kg surface blast will reach a depth of 0.8 m. The stresses from a surface blast are larger than those from a suspended blast (Miller et. al, 2011). Since a smaller charge size was used in this study, measurements made to a depth of 1 m were expected to capture any changes. Snow pit width was just wide enough to allow for data collection.

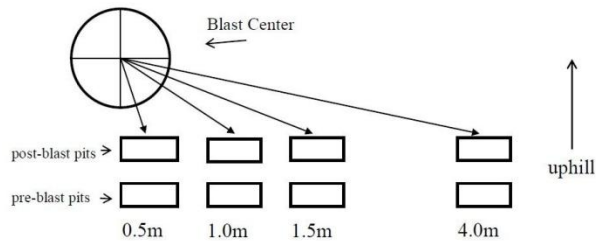


Figure 1: Diagram of sampling design, showing the pre- and post-blast pit locations and blast center. Pre-blast pits were located 0.5 m downhill of indicated distances in order to leave undisturbed snow at 0.5, 1, 1.5 and 4 m from the blast center for post-blast sampling.

Snow density was assessed in 10 cm increments with the first measurement taken at a depth of 5 cm from the snow surface. Density was measured using a Winter Engineering snow density gauge equipped with a 100 cc cylindrical cutter and a mass balance gauge reading from 0% to 60% water content. Accuracy and variability of density measurements were evaluated through lab tests, but discussion of these results is outside the scope of this paper. Compression Tests (CTs) were performed for 25 of the 27 detonations. For each of those 25 tests, CTs were conducted at two of the four snowpit localities that were dug at various distances from the blast center. After conducting 9 air blast tests, the locations of CTs were changed from 0.5 m and 1.5 m from the blast center to 1 m and 4 m in order to better explore the spatial changes in snow properties with greater distance from the blast center.

After initial setup and pre-air blast measurements were completed, a 0.9 kg cast pentolite booster was taped to the bamboo located at the blast center. The center of the booster was positioned exactly 1 m above the snow surface in keeping with current industry standards and with the closed end of the blasting cap oriented in the downward direction. After explosive detonation, distances from the blast center to the snowpits were re-measured, new pits were dug and all measurements were repeated.

### 2.3 *Data Analysis*

Before- and after-blast density measurements were correlated both from the snow surface down and the ground up and examined separately to determine whether the same trends were present. This additional analysis was undertaken to ensure that similar trends could be replicated regardless of the starting point for comparison of the pre- and

post-blast density of individual layers. The data were initially plotted as box and whisker plots, displaying the median, interquartile range and maximum range. Once these plots had been reviewed the data were tested to assess if the observed changes in density were statistically significant. Not only did the data violate the assumption of continuity, but normal probability plots showed deviation from normality, histograms showed some skewness, and Lilliefors tests of normality indicated non-normal distributions. Therefore, the non-parametric Wilcoxon sign-rank test was used to test for a significant change in snow density. Changes in the number of taps at column failure and changes in shear quality were examined for CTs at all distances from the blast center. The Wilcoxon sign-rank test was used to test for a statistically significant change at 1 m and 4 m from center. Data from CTs at 0.5 m and 1.5 m from center were not tested for statistical significance because of the small number of measurements ( $n=9$ ).

### 3. RESULTS

Density change data correlated both from the surface down (Figure 2) and the ground up indicate at least a small density increase for almost all of the sampled locations. Results from statistical tests of data correlated from the surface down indicate that density increases significantly in the region extending out to a distance of 1.5 m from the blast center and down to a depth of 60 cm below the snow surface (Table 1). Significant density increases are also evident deeper in the snowpack out to 1.5 m from the blast center (Table 1). After explosive detonation the number of CT taps at both 1 m and 4 m from the blast center decreased (Figure 3). Statistical test results suggest no median change in CT results at 1 m from the blast center, but at 4 m from center there is a statistically significant decrease in CT taps (Table 2). Shear quality data from CTs at 1 m from the blast center show no median change, but 75% of the observations show zero change or a decrease in shear quality defined by an increase in Q number and a less sudden, less planar shear (Figure 4). This result is validated by field observations of cracks, holes and obvious discontinuities in the snowpack 1 m from the blast center after detonations. The data show no median change in shear quality for CTs at 4 m from the blast center, and 81% of observations at this distance also indicate zero change (Figure 4).

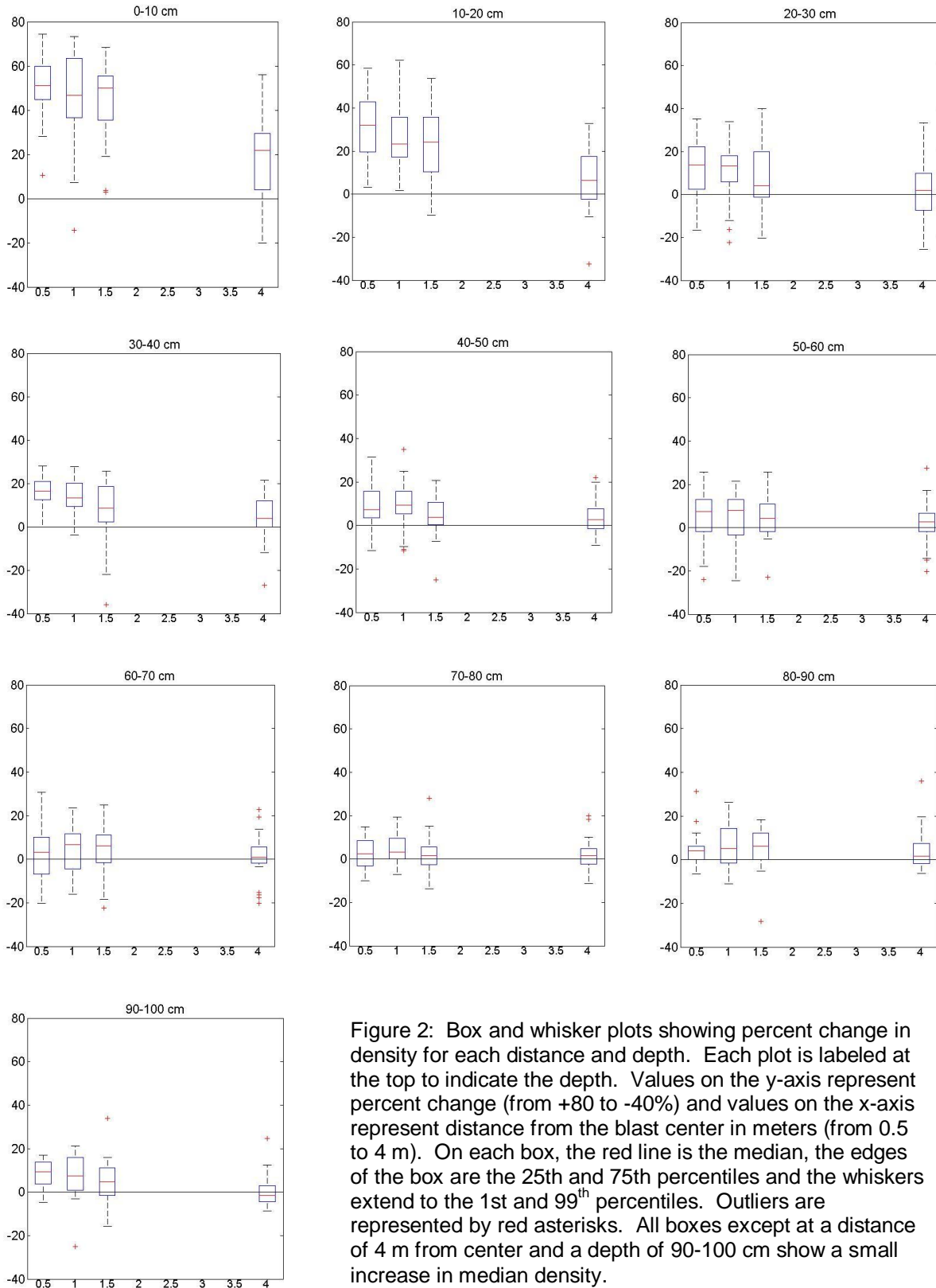


Figure 2: Box and whisker plots showing percent change in density for each distance and depth. Each plot is labeled at the top to indicate the depth. Values on the y-axis represent percent change (from +80 to -40%) and values on the x-axis represent distance from the blast center in meters (from 0.5 to 4 m). On each box, the red line is the median, the edges of the box are the 25th and 75th percentiles and the whiskers extend to the 1st and 99<sup>th</sup> percentiles. Outliers are represented by red asterisks. All boxes except at a distance of 4 m from center and a depth of 90-100 cm show a small increase in median density.

Table 1: P values generated from the Wilcoxon sign-rank test, testing percent change in density data for a median of zero. P values less than 0.05 are shaded and indicate a statistically significant change in density. Layers are correlated from the snow surface down. Data sets contain 26-27 measurements except where indicated. Small sample sizes are a result of snow loss/compaction or shallow snow cover.

Depth↓ Distance→	0.5m	1m	1.5m	4m
0-10cm	5.5670e-006	5.5497e-006	5.6061e-006	1.0811e-004
10-20cm	5.5974e-006	5.6018e-006	3.0241e-005	0.0146
20-30cm	1.5656e-004	0.0023	0.0184	0.5484
30-40cm	1.2257e-005	9.8065e-006	0.0143	0.0533
40-50cm	2.5270e-004	0.0022	0.0034	0.0261
50-60cm	0.0490 (n=25)	0.0182 (n=25)	0.0124	0.0926
60-70cm	0.4929 (n=22)	0.0666 (n=24)	0.0714 (n=24)	0.3299 (n=25)
70-80cm	0.2237 (n=22)	0.0149 (n=24)	0.3506 (n=24)	0.4379 (n=25)
80-90cm	0.0244 (n=14)	0.0279 (n=19)	0.0108 (n=20)	0.0766 (n=22)
90-100cm	0.0234 (n=8)	0.0771 (n=13)	0.1099 (n=13)	0.9794 (n=17)

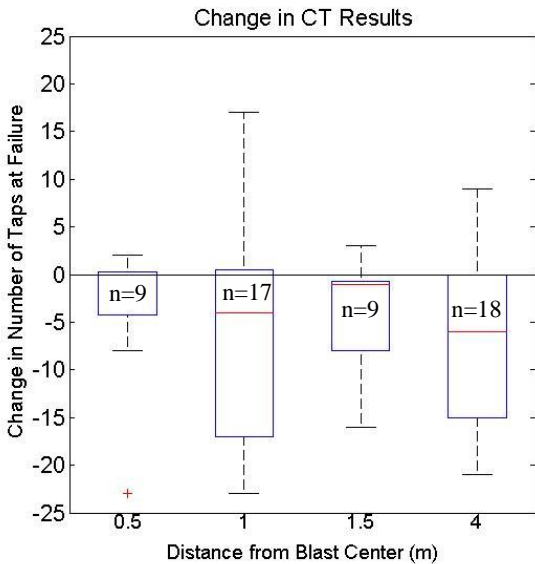


Figure 3: Box and whisker plot showing change in CT results and demonstrating change in number of taps at column failure at all tested distances from the blast center. On each box, the red line is the median, the edges of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentiles and the whiskers extend to the 1<sup>st</sup> and 99<sup>th</sup> percentiles. Outliers are represented by the red asterisks

Table 2: P values generated from the Wilcoxon sign-rank test, testing change in CT score for a median of zero. P values less than 0.05 are shaded and indicate a statistically significant change in CT score.

Test Type	1 m	4 m
CT	0.0674	0.0082

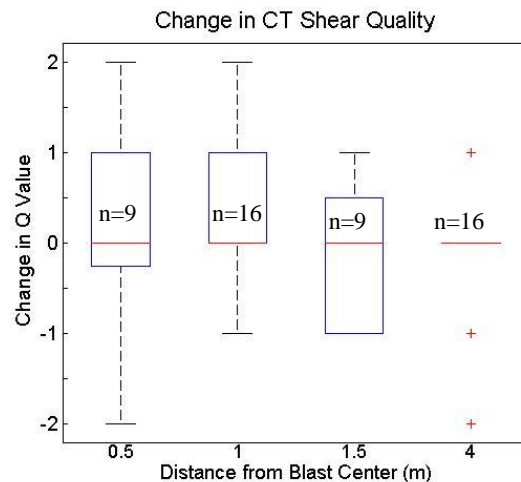


Figure 4: Box and whisker plot showing change in shear quality at all distances from the blast center for CTs at each location. An increase in Q number indicates a decrease in shear quality and a less sudden, less planar shear. Box parameters are the same as in Figures 2 and 3.

#### 4. DISCUSSION

These findings are the first experimental field-based observations of changes in snow density due to explosives and indicate that the effects of explosives may extend slightly beyond the depths predicted by Miller et al. (2011). These results show an increase in density and suggest that the explosives continue to affect snow to a depth of 1 m directly below the blast center, and a depth of 90 cm at distances of 1 m and 1.5 m from the blast center. These results should be interpreted with care due to the small sample sizes at depths of 80-100 cm and distances out to 1 m from the blast center. It should be noted that percent increases in density are not always greatest near the blast center. This could be a sign that there is a similar effect over this whole area (extending out to 1.5 m) regardless of proximity to the blast center. Density increases occurring at a distance of 4 m from the blast center, suggest that explosives have limited effect on density except in the upper snowpack at this distance. These measurements provide field based observational data that could be incorporated into future predictive models to produce a more robust picture of explosive effects on snow and the area affected.

Snow height decreased in the region near the blast center, therefore small inconsistencies in layering in before- and after-blast measurements occurred. The layer identifiers measured from the snow surface down rather than the ground up were included in these results for two key reasons. It was more important to accurately match layers at the top of the snowpack because presumably there should be a greater effect closer to the blast center. Additionally, over 900 before- and after-blast density measurements demonstrated an improved correlation in layers when matched from the surface down. Furthermore, analysis undertaken comparing pre- and post-blast metrics as measured from the bottom up displayed similar trends to those presented here from the top down.

Significant decreases in CT taps at 4 m, but not at 1 m from the blast center; and poorer shear quality at 1 m, but not at 4 m from the blast center imply that the shock wave may be disrupting the failure plane or the consistency of the slab in the immediate area (1.5 m) of the blast. A clear and continuous region of density increase affecting depths to 60 cm and extending out to 1.5 m from the blast center could hint at a change in slab consistency. As noted above, density is observed to increase beyond this area, however it is more

patchy beyond this specific region. Because densification of snow occurs higher in the snowpack, slabs may be gaining strength, while the underlying snow is not, adding to the overall instability. However, simultaneously, decreasing shear quality is observed in the region with the greatest increases in density which may be compensating for this effect and inhibiting failure at weak layer interfaces. Observation of the snowpack after field tests exposed cracks, holes and wandering fractures within the snowpack at all distances from the blast. These are an indication of discontinuities in the snowpack which could arrest fracturing on a horizontal plane. These observations support the theory that the use of explosives is likely to be effective in disrupting the failure plane. Carvelli (2008) highlighted this idea of failure plane disruption as part of the rationale for bootpacking and systematic explosives use at Aspen Highlands and Kronholm and Birkeland (2005) use a model to demonstrate how such disruptions might increase overall stability.

#### 5. CONCLUSION

These findings are the first field-based observations that show changes in the physical properties of snow that occur as a result of explosives use. The results here demonstrate a statistically significant increase between pre- and post-blast snow density. However, snow stability test scores as measured using a CT showed decreases, with larger decreases occurring farther from the blast center. Larger changes at farther distances are counterintuitive at first. However, observations suggest that the shear plane at shorter distances was disrupted, and this may have resulted in slightly higher test scores than if the shear plane had been unaffected. At farther distances, observations indicate that the shear plane was still relatively intact and the taps to failure decreased more than at the closer distances.

These results provide new information to avalanche practitioners and will hopefully enable a better understanding of how explosives affect snow densities and snow stability. Future work should include repeated explosives tests with measurements at distances between 1.5 m and 4 m from the blast center. A more continuous data set may give a better view of density change over the entire 4 m area. Additional tests should also include Extended Column Tests (ECTs) (Greene et al., 2010) to provide a more comprehensive data set of stability tests.

## 6. ACKNOWLEDGEMENTS

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## 7. REFERENCES

- Brown, R.L., 1981. A method for evaluating shockwave propagation in snow. *Cold Regions Science and Technology*. 5, 151-156.
- Carvelli, P., 2008. Boot Packing and "Systematic application of explosives": Shear plane disruption techniques in the continental climate. *Proceedings of the International Snow Science Workshop*. Whistler, 2008. 337-344.
- Frigo, B., Chiaia, B., Cardu, M., Giraudi, A., Godio, A., Rege, R., 2010. Experimental analysis of snowpack effects induced by blasts. *International Snow Science Workshop*, Squaw Valley. 66-71.
- Greene, E., D. Atkins, K. Birkeland, K. Elder, C. Landry, B. Lazar, I. McCammon, M. Moore, D. Sharaf, C. Sternenz, B. Tremper, and K. Williams., 2010. *Snow, Weather and Avalanches: Observation Guidelines for Avalanche Programs in the United States*. Pagosa Springs, CO, Second Printing Fall 2010: American Avalanche Association.
- Gubler, H., 1977. Artificial release of avalanches by explosives. *Journal of Glaciology*. 19:81, 419-429.
- Kronholm, K. and K.W. Birkeland. 2005. Integrating spatial patterns into a snow avalanche cellular automata model. *Geophysical Research Letters*. 32, L19504, doi:10.1029/2005GL024373.
- Lamond, J.L., 2006. Significance of tests and properties of concrete and concrete making materials. West Conshohocken: ASTM.
- Livingston, C.W. Explosions in snow. Technical Report 86, Hanover: USA CRREL, 1968.
- Lyakhov, G., Salitskaya, V., Averchenko, A., Zakharov, S., Bakhushina, L., 1989. Explosive waves in snow. *Combustion, Explosion and Shock Waves*. 25: 4, 493-499.
- McClung, D. and P. Schaerer, 2006. *The Avalanche Handbook*. Seattle: The Mountaineers Books.
- Mellor, M., 1968. *Avalanches*. monograph, Hanover: USA CRREL.
- Mellor, M., 1973. Controlled release of avalanches by explosives. General Technical Report RM-3. US Department of Agriculture, Forest Service. 137-49.
- Miller, D.A., Tichota, R.G., Adams, E.E., 2011. An explicit numerical model for the study of snow's response to explosive air blast. *Cold Regions Science and Technology* 69, 156-164.
- Ueland, J., 1992. Effects of explosives on the mountain snowpack. *International Snow Science Workshop*, Breckenridge. 205-213.
- Wisconsin Geological and Natural History Survey, 2011. Rock properties: Porosity and density. <http://wisconsingeologicalsurvey.org> (accessed July 17, 2012).
- Wisotski, J. and Snyer, W.H., 1966. A study of the effects of snow cover on high explosive blast parameters. Final Report submitted to United States Naval Ordnance Laboratory, Air-Ground Explosions Division, Denver: Denver Research Institute - University of Denver.