THE EFFECTIVENESS OF BOOT PACKING FOR SNOWPACK STABILIZATION

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ABSTRACT**:** Depth hoar is a persistent weak layer that is a common instability problem in the snowpack of many areas around the world. Boot packing or compaction via explosives is a technique that is widely used in an attempt to disrupt this weak layer and increase its variability across a slope, thereby increasing overall slope stability. While some data have been gathered on the results of boot packing and explosive use on slopes, no recent work has concentrated directly on the effect of boot packing on layer density, hand hardness and stability test scores. Therefore, we devised an experiment to test the changes in these metrics directly on a side-by-side boot-packed and non-boot packed slope.

A 50m x 25m, relatively uniform slope was split into two equal areas with one being extensively boot-packed, while the other remained undisturbed. Observations were made in both boot packed and non-boot packed plots until both areas were unreactive with respect to results using Extended Column Tests (ECT) on this basal layer. Our results show that density and hand hardness increased in the boot packed area in comparison to the non-boot packed area. Furthermore, in the boot packed area we also observed a marked increase in ECT scores and a change in fracture character of the basal layers. In the non-boot packed area our ECTs propagated (ECTPs) for a full nine weeks longer than in the boot packed area. While this is just one case study, we are encouraged by our results, which provide quantitative data that indicate that boot packing can be an effective tool for helping to stabilize persistent basal weak layers.

1. INTRODUCTION

Persistent basal weak layers such as depth hoar pose a distinct problem for operations that try to open avalanche terrain. These layers are often spatially continuous at the slope scale, and without intervention are often undisturbed. Kronholm and Birkeland (2005) modeled increasing stability with increasing weak layer variability and suggested that this might be a primary way that boot packing helped to stabilize slopes. To reduce instability, these layers must be disrupted at a scale of every meter or less (Schweizer et. al., 2008). Boot packing or selective explosive placements are forms of mechanical compaction that attempt to disrupt the continuity of this layer while also trying to increase the spatial variability of the layer (Carvelli, 2008).

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By disrupting the spatial homogeneity of the slope and compacting the depth hoar, an attempt is made to create a ‘more stable’ slope. Once the early season application of boot packing has been completed, it is rare that the same slope will once again receive any significant and widespread compaction or layer disruption near the base. With subsequent skier and/or explosive disruption of new layers on top of the boot packed area, a non-homogenous snowpack can usually be achieved. With this application of skier compaction, as typically used in an operational setting, it is difficult track changes in layer density and hardness over the course of a winter to see what changes, if any, are occurring in these basal layers. Changes in the upper snowpack properties and stability tests are also difficult to monitor.

While boot packing has been performed at various ski operations, with incentives provided to the public to assist with the task (e.g. a free season’s pass for 5 days of work), its use outside of these operations has been minimal. Furthermore, despite this industry use, there has been limited published data showing whether or not a simple application of boot packing can improve the slope stability for areas that do not have any additional disruption via rider traffic, explosives or other means. One of the few published studies is by Carvelli (2008), who stated that a review of avalanche occurrence records at Aspen Highlands indicate no avalanches initiating in or penetrating into dry boot packed layers since the program's inception in 1988. However, no quantitative analysis has been done on the effects of boot packing on basal snow densities**.**

Therefore, the focus of this study is to look at how mechanical compaction (via boot packing) of a persistent weak layer of depth hoar during the early part of a winter season affects basal layer density and hand hardness on a protected and undisturbed study plot. These metrics will be compared to a non-boot packed slope immediately adjacent to the boot packed slope. Propagation potential and fracture character via the Extended Column Test (ECT) will also be analyzed on both slopes, with a particular emphasis on examining how the altered snowpack changes the results and its implication for slope scale stability.

2. METHODS

A study site was chosen within the Moonlight Basin Ski Area boundary at Big Sky, Montana, USA. The site was chosen because it is below tree line (2423 m (7949 ft)), thereby reducing the effects of the strong winds the area typically receives at tree line and in the alpine, but at the same time high enough to receive a sufficient snow to provide a consistent addition of load onto the study plot throughout the ski season.

This easily accessed site was also chosen for its consistent and uniform Northwesterly aspect (300°) that would produce strong temperature gradients for the formation of depth hoar and also help to reduce solar effects during the spring. The site also features a consistent pitch (average of 14°) and ground cover, as this is a currently closed future ski run created with heavy equipment. Ground roughness consists of compacted scree and dirt and varies little over the entire plot. These features, while providing a uniform test slope, also lend to a more uniform snowpack than one would typically see in an avalanche start zone at the ski area.

Once a depth hoar layer was verified to be within the study area in late December of 2011, a 50 meter wide by 25 m vertical study plot was marked out to create two equal 25 meter squares ($625m^2$). On December 20, 2011, the Northerly plot was heavily boot packed using spacing between boot pack lines of 15cm or less and with a normal walking stride (figure 1). Boot packing depths on average penetrated near (within 5cm), or to the ground. A full snow profile that included densities (taken with a Winter Engineering 100cc snow density gauge) and ECTs was excavated and recorded according to Greene et al. (2010) on the non-boot packed side for baseline data. For the next 76 days, test profiles which included snow stratigraphy (hand hardness index, grain form, 10 cm density increments and ECTs) were taken on both study plots at 7 to 10 day intervals and recorded. Data collection ceased once propagation was again observed in the boot packed study plot.

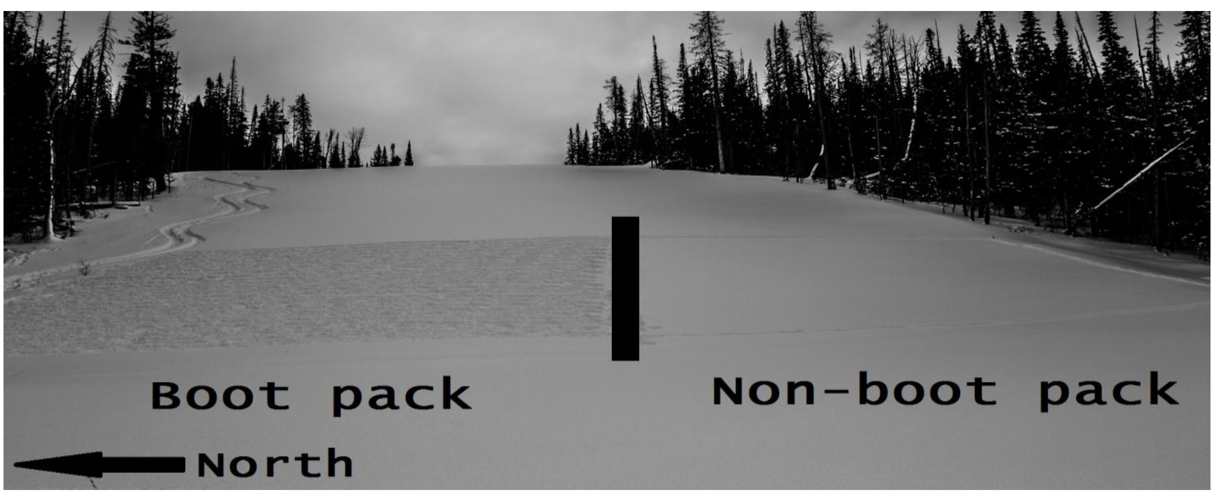

Figure 1: Study plot showing boot pack and non-boot pack sides. December 26, 2011. Each area is approximately 25m x 25m.

3. RESULTS AND DISCUSSION

Our results show that there is an increase in both hand hardness and density of the boot packed layers. Five of the lowest depth divisions were placed in a box plot to note differences in densities (figure 2). Of note are the 0 cm to 10 cm and 10 cm to 20 cm where the most changes in density were noted. An average 80 kg/m^3 increase in density was noted in the bottom 10 cm followed by a noticeable increase in the next 10 cm increment. These depths were the target layers for the study as this is about the maximum vertical extent the depth hoar was found. It is also worth noting that the layers above this, (i.e. 20-30 / 30-40 and 40-50cm) have a median difference near zero which indicates that we observed the same snow layer, with similar densities on both the boot packed and non-boot packed plots. In all but one occurrence, this increase in density was found for the entirety of the study.

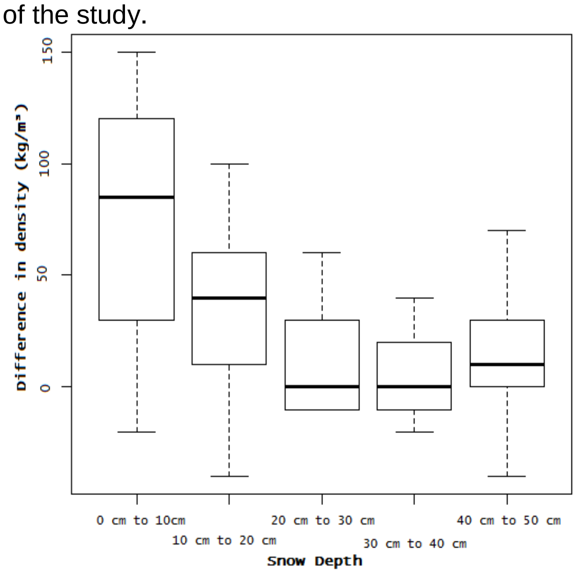

Figure 4: Box plot showing the difference in density (Kg/m^3) for the boot packed vs. the non-boot packed slopes, for the lowest 5 test distances in 10cm increments. The bold line represents the median, while the box is the 25th and 75th percentile, and the whiskers represent the full range of the observed values.

Using the Wilcoxon Signed Rank test to compare ground to 10cm densities, the results show that there is a significant difference (N=10: $p \leq .01$) between the boot packed and non-boot packed basal layers. When we grouped the ground to 10 cm and 10 cm to 20 cm layers and compared, the results remain statistically significant (N=20, $p \leq .001$).

A steadily increasing density of the basal boot packed layer was observed until reaching a maximum density of ~330 kg/m^3 (figure 3) in March during the beginning of the spring time in this area. Of note are the steadily decreasing densities of the undisturbed site until early February when there begins to be a slow gain in density. This reduction in density is consistent with our observations and understanding of depth

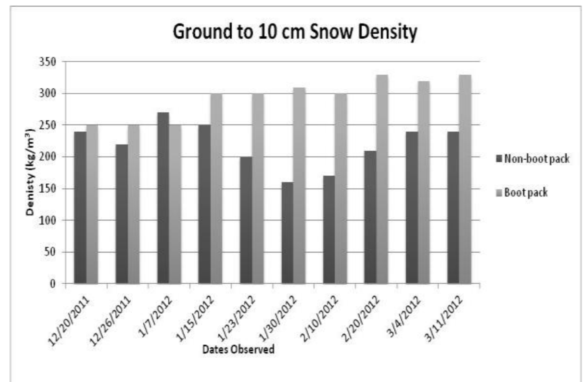

Figure 2: Graph showing the progression of densities in the lowest 10cm of the snowpack in the boot packed and non-boot packed areas during the study period.

hoar growth and the "rotting out" of the snowpack under continued high temperature gradient conditions. When the density of the depth hoar in

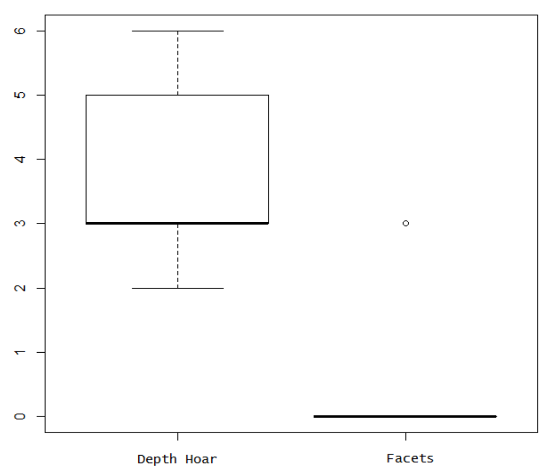

Figure 3: Box plot showing the difference in hand hardness of the depth hoar and facet layers for the boot packed vs. the non-boot packed slopes. The bold line represents the median, while the box is the 25th and 75th percentile, and the whiskers represent the full range of the observed values.

the non-boot packed area was at its lowest, the density of the boot packed area was double that of the non-boot packed area. After this date the non-boot pack density increased, but always remained well below (at least 70 kg/m^3 below) the boot packed side.

The difference in layer hardness between the boot packed and non-boot packed areas far exceeded the differences in an overlying faceted layer (figure 4). One reason for this is that these layers varied in thickness and cannot be directly correlated to a 10 cm layer of densities except in the boot packed area. Hand hardness was broken into numbers using F=1, 4F-=2, 4F=3, etc. Again, using the Wilcoxon Signed Rank Test, there was a significant difference (N=8, $p \leq .001$) between the change in hardness for the depth hoar when compared with the facets. Hand hardness changed very little within the overlaying facets but layer depths of these facets did vary.

ECTs were conducted for the duration of the study with two tests per side conducted each study day (table 1). Fracture propagation is seen in the non-boot packed area all season while in the boot packed area, propagation is not seen until March 4 (shaded in table 1). This is almost an 11 week difference where the boot packed area shows no propagation. From the initial test pit until March 4 (when the boot packed area show propagation) the non-boot packed plot produced propagation on the DH layer with sudden collapse fracture character. It was not until after we observed propagation on the boot pack side that the non-boot pack side shifted from having the failure on the DH layer to a failure in the upper part of the FC layer (~40 cm thickness) immediately above the DH. This layer failed with easy taps but fracture character was resistant planer in both areas. At this time both study areas began to fail in the upper 1/3 of the snowpack and continued this for the next study date at which time record keeping ended. At this stage we considered the effect of boot packing / non-boot packing to no longer be important. This long time period before the boot pack area became reactive again (on a higher layer) represents a potential 11 week difference in useable terrain as a result of boot packing on this basal layer.

Table 1: Showing the ECT results from the collection days.

Date	Non-boot pack		Boot pack	
	Test 1	Test 2	Test 1	Test 2
12/20/2011	ECTP 11	ECTP13	EXTX	ECTX
12/26/2011	ECTP 8	ECTP 8	EXTX	ECTX
1/7/2012	ECTP 10	ECTP 11	EXTX	ECTX
1/15/2012	ECTP 12	ECTP 13	EXTX	ECTX
1/23/2012	ECTP 15	ECTP 16	EXTX	ECTX
1/30/2012	ECTP 3	ECTP 4	ECTN 16	ECTN 16
2/10/2012	ECTP 12	ECTP 11	ECTX	ECTX
2/20/2012	ECT 11	ECTP 11	ECTX	ECTX
3/4/2012	ECTP 4	ECTP 3	ECTP4	ECTP 5
3/11/2012	ECTP 11	ECTP 11	ECTP 11	ECTP 11
Failure Depth:		Depth Hoar		
		Facets		
		Upper 1/3 of Snowpack		

An important aspect that we did not thoroughly investigate was the heterogeneous nature of the upper interface of the compacted depth hoar layer. While difficult to map and not part of this study, we observed that it was a nonplanar layer with differences of up to 15 cm in this basal layer as a result of the boot packing. This resulted in a disrupted and poor shear plane for the FC layer above, which obviously had an impact on the ECT results. The disruption of the failure plane is one goal of boot packing and is consistent with work by Carvelli, (2008) with respect to shear plane modification using explosives. The disrupted failure plane increases the likelihood for fractures to arrest before growing to the critical size necessary for releasing an avalanche (Kronholm and Birkeland, 2005).

4. CONCLUSION

Our results demonstrate that mechanical compaction of snow via boot packing results in a statically significant increase in both density and hand hardness of basal depth hoar. By using early season boot packing we can change the strength and properties of this persistent weak layer. ECTs in boot packed areas did not propagate (ECTN) for 11 weeks during which non-boot packed areas did propagate (ECTP). This potentially represents an 11 week difference in useable terrain due to boot packing. One positive outcome of our work is that our results suggest that operations that lose pieces of terrain due to full depth avalanches to ground may be able to boot pack that terrain, thereby securing the opening of these areas while only dealing with new snow instabilities. While this was just one study conducted under certain conditions, our work does show that boot packing is an effective tool for disrupting basal weak layers, thereby increasing the stability of those areas.

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