THE EFFECTS OF COMPACTION METHODS ON SNOWPACK STABILITY

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ABSTRACT: The interaction between snowpack layers determines the snowpack stability. It follows that disrupting layers may improve stability. Ski patrols and guiding operations employ mechanical compaction methods such as boot packing, ski compaction, and explosives aiming to increase snowpack stability. High-usage backcountry areas (but still uncontrolled avalanche terrain) may become compacted, developing a snowpack with different characteristics than in lower usage adjacent terrain. A challenge in avalanche forecasting is determining how this compaction alters snowpack stability, if at all.

Our results show that snow pack stability increases if compaction penetrates and impacts a weak layer, disrupts the failure plan, or affects slab cohesion. This is likely due to an increased probability of fracture arrest in a compacted snowpack from either slab or weak layer heterogeneity. While several compaction methods exist, specific research addressing different compaction techniques is lacking. This study compares the effects of different compaction methods on a snowpack. The snowpack for our case study consisted of an approx. 30 cm 1F wind slab over approx. 30 cm depth hoar. After applying mechanical compaction methods to nine slopes, we conducted ECTs and PSTs over six weeks to assess stability. We found ECTXs more common in compaction-dense areas (boot packed) than in compaction-light (skied and compaction free) areas.

This research quantifies some of the effects of different compaction strategies, and provides preliminary guidance for avalanche practitioners on the most useful techniques for mitigating avalanche hazard.

KEYWORDS: compaction, snowpack stability, stability test, boot-packing, ski compaction

1. INTRODUCTION

Natural compaction occurs within a mountain snowpack due to snow metamorphism, wind, and settlement. Temperature, liquid water content, and layer depth are major factors which drive natural snow pack compaction. Compaction is a natural process of the winter snowpack; compaction over multiple seasons eventually produces glacier ice (Armstrong and Brun, 2008).

Mechanical compaction is the result of a non-natural settlement and impact to the snowpack – skiers, explosives, snow machines, etc. Mechanical compaction is a quicker, but more localized process of snowpack compaction. Mechanical compaction deforms the snowpack by disrupting snowpack layers. The resulting heterogeneous snow structure may increase snowpack strength and also may enhance fracture arrest (Kronholm and Birkeland, 2005). The resulting effect of mechanical compaction on snowpack stability is dependent on the depth of the compaction, the vertical position of weak layers within the snowpack, the amount of compaction, and the coverage of the compaction throughout an area.

Ski patrols and guiding operations employ mechanical compaction methods such as boot packing, skiing, and explosives aiming to increase snowpack stability. Compaction methods are intended to disrupt the shear plane of potential avalanches and decrease the cohesiveness of possible slab layers (Carvelli, 2008). Our research

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seeks to address how mechanical compaction may affect snowpack stability in uncontrolled avalanche terrain.

Compaction efforts such as boot packing, ski cutting, and explosives begin in controlled avalanche terrain as soon as the first snow falls. Aspen Highlands in Colorado has employed systematic mechanical compaction (bootpacking, explosives, etc.) in specific avalanche terrain for over 20 years effectively eliminating the occurrence of large avalanches in such terrain (Carvelli, 2008). Furthermore, preliminary work by Wieland et al. (2012) suggests that compaction can be successful in removing the instability from a basal weak layer as measured with an Extended Column Test (ECT). Their work suggested that effective boot packing can result in several weeks of difference between ECT N (arrest) and ECT P (propagation) results (9 weeks in their study). The end result of avalanche control methods (compaction by boot packing, skiers, and explosive testing) is to create a non-stratified snowpack by completely disrupting or destroying any potential sliding layer or interface, resulting in only surface instabilities created by new snow and wind (Carvelli, 2008).

With increased backcountry usage, the snowpack in popular skiing areas can quickly become compacted, though not nearly as heavily compacted as the snowpack within a ski area. Variable usage patterns, such as increased use on weekends or holidays, can produce a different snowpack than in the surrounding areas and regional avalanche forecast. A concern for some backcountry forecasters is the development of a false sense of avalanche knowledge and confidence in recreationalists who learn and progress in such high-usage backcountry areas. As users progress and explore, they eventually leave such high use areas and move into less-compacted terrain, where the regional avalanche forecast is more representative and the snowpack more variable. A major challenge presented to avalanche forecasters is how to communicate avalanche hazard in a region that has both areas with minimal usage and compaction and areas that have extremely high usage and a heavily disturbed snowpack. To date, there is little research focusing on the effects of different methods of mechanical compaction on snowpack stability. This research examines the effect of three different methods of compaction (bootpacking, ski compaction, and skiing) on snowpack stability. Our aim is to provide preliminary guidance for avalanche practitioners on methods for assessing snowpack stability in compacted terrain.

2. STUDY AREA AND METHODS

The study area is a summer road within the boundaries of the Yellowstone Club in SW Montana, USA. The site is a planar slope with an average slope angle of 10 degrees below tree line at an elevation of 2690 m on the west side of the ski area. The. Access to the site was restricted and no unaccounted tracks were recorded. Along the road 13 plots (1 - 10 m x 10 m study plot and 12 - 5 m x 5 m test plots) were isolated and marked with rope (Fig. 1).

Fig 1: The study area at the Yellowstone Club. 5 m x 5 m study plots are identified by color: Ski – red; Compaction Free – yellow; Ski Compaction – green, Boot Pack – blue. The 10 m x 10 m study plot is outline in black. Aspect is W-SW; slope angle varies from 8-15 degrees.

Test plots were divided into three groups of four. Each group contained three different compaction method plots (Boot Pack, Ski Compaction, Ski) and one plot with no compaction (Compaction Free). The Boot Pack test plots were compacted so that footprints were spaced no more than 20 cm from each other. The Ski test plot was skied through 5-6 times with two turns such that it would be considered ‘tracked out’ in a back country setting. Ski Compaction test plots were side-stepped so that the entire surface had been compacted by a ski. Mechanical compaction was performed by three individuals 68-77 kg, on skis 108-120 mm underfoot.

Each compaction method was used in three plots (a total of nine compaction plots). At this time, the 1 m deep snowpack structure consisted of basal facets and depth hoar buried under a denser mid-pack and low-density surface snow. A layer of interest was identified approximately 30 cm above the ground where a 1F wind slab sat on basal facets and depth hoar. Following the one-day compaction event, access was restricted to the entire area. Figure 2 displays a Compaction Free and Ski plot.

Over the course of six weeks (January 7 - February 17, 2016), nine field days occurred. A field day consisted of a full profile in the undisturbed study plot and four test profiles in one group of plots (three different compaction method plots and one compaction free plot). A single observer conducted every test for consistency and followed the standard procedure for Extended Column Tests (ECT), Propagation Saw Tests (PST), and Compression Tests (CT) (ORGS 2014, SWAG 2010). A test profile included layer identification and hardness, 10 cm snow density measurements, one CT, two ECTs, and one PST. Including the study plot, 90 ECTS, 45 CTs, and 35 PSTs were collected over nine field days.

Fig. 2: Compaction Free and Ski 5 m x 5 m plots. January 7, 2016

3. RESULTS

For this paper, we focus on the overall ECT and PST results and the danger rating provided by the Gallatin National Forest Avalanche Center (GNFAC). In an effort to provide relevance to current practices only a sample of our results will be presented with a more complete analysis to be presented later. One specific area of interest is the effectiveness of boot packing against skier compaction and the duration of time for which one is more effective than the other.

On all field days, the GNFAC rated the hazard in the Madison range either Moderate or Considerable (GNFAC, 2016). A weak basal facet layer below a dense slab was a constant concern. We found this layer 24-38 cm above the ground in the Study Plot. All ECTs and PSTs tested this layer.

Our results suggest that compaction dense methods (e.g. boot pack, ski compaction) are more effective than compaction-light methods (e.g. skiing) for this particular snowpack structure. We used ECT and PST results to index snowpack stability and interpret results (Ross and Jamieson, 2008) (Gauthier and Jamieson, 2008).

3.1 *Extended Column Test Results*

Ten ECTs were performed across five plots daily (Study Plot, Compaction Free, Ski, Ski Compaction, and Boot Pack). Over the nine field days, a total of 90 ECTs were performed. Overall, Boot Pack plots had the most ECTXs (13 of 18 – 72%), suggesting the lowest chance of propagation on a given day. The Compaction Free and Ski plots had the most ECTPs (both with 10 of 18 – 56%) and the Compaction Free had the fewest ECTXs (3 of 18 – 17%) (Fig. 3).

Total depth of the snowpack (HS) increased from approximately 95 cm at the top in the Study Plot to an average of 118 cm in the test plots at the bottom of the study area at the beginning of the study (Fig. 1). A large difference in overall ECT scores was observed between the Study Plot (compaction free) and the Compaction Free test plots (Fig. 3), with a larger proportion of propagating ECTs in the test plots. We propose that this is due to the spatial variability of HS along the length of the study area – with much shallower snow at the study plot, and relatively deeper snowpack test plots at the bottom of the study area. ECT results indicating poor stability were observed in compaction-free and compaction-light (Ski, Ski Compaction) plots.

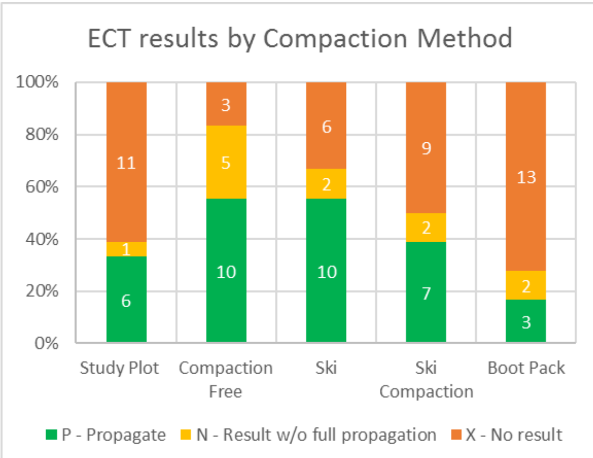

Fig. 3: ECT Results for the Study Plot and Test Plots as a function of the compaction methods.

3.2 _Propagation Saw Test Results_

A total of 35 PSTs were performed on the identified layer of interest (approx. 30 cm above the ground). Every PST resulted in propagation to the end of the column (PST End). For all compaction methods, 45 cm was the average PST cut length (Fig. 4). The Boot Pack plots had the longest average cut length of 59 cm.

The Compaction Free plot recorded the second longest average cut length of 48 cm. In contrast, the Study Plot produced the shortest average cut length of 36 cm. In contrast, the Study Plot ECT scores indicated a more stable snowpack than the Compaction Free plots.

4. DISCUSSION

Our study shows three methods of compaction had notably different impacts on stability, as indexed with the ECT and PST results. ECTX results increased as compaction methods became more penetrative, with boot packed plots having the greatest proportion of ECTXs. Most striking is the large difference in ECT scores between Boot Pack and the Compaction Free plots.

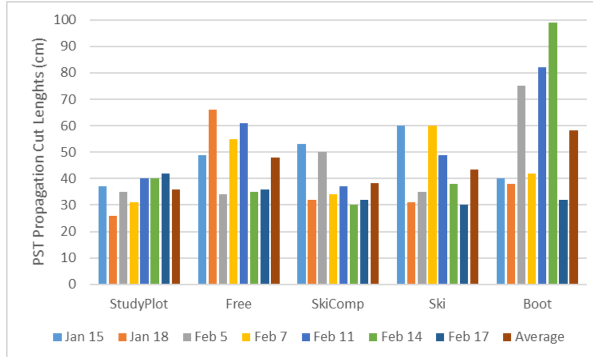

Fig. 4: PST Propagation cut lengths by compaction method

A similar study found a notable increase in ECT scores and poor fracture character in boot packed terrain compared in compaction-free terrain (Wieland, et. al, 2012). In their study, ECTs in compaction-free terrain propagated a full nine weeks longer than in the boot packed terrain. Our study produced more mixed results. Boot Pack plots were less reactive compared to other plots. However, our compaction methods did not completely eliminate the weak layer.

In some cases, ECT results in Boot Pack and Ski Compacted plots resulted in breaks within the compacted layer. These breaks sometimes resembled a boot print or ski track. Such breaks were also documented by the Aspen Highlands bootpacking program (Heinecken, 2004). In our study, at times boot packing and ski compaction methods appeared to produce higher density and more cohesive blocks of snow. These results, along with the lack of similar results in the Ski plots, suggest that the concentration and density of the disruption are also important in compaction.

Compaction methods at Aspen Highlands stress that shear plane disruption is the primary goal of compaction measures (Carvelli, 2008). In order to achieve this, compaction measures begin early in the season. In our study, compaction methods were applied in January to an approximately 1 m deep snowpack with a weak layer buried by 70 cm of snow. We also noted a gradual increase in HS downslope through the study area. Compaction methods were less effective downslope in the relatively deeper snowpack. Shear plane disruption was not always achieved as compaction methods did not penetrate deep enough into the snowpack. In some compacted plots (Ski Compaction), we increased the density and cohesion of the slab above the layer of concern, while not impacting the weak layer. In other compacted plots (Boot Pack), we had more success with compaction penetrating to the weak layer and resulting in more ECTXs.

5. CONCLUSION

This study assessed the impact of different compaction methods on a particular weak layer. We conducted ECTs and PSTs in areas with varying amounts of compaction and compared those results to danger ratings in regional avalanche advisories. Overall, tests in heavily compacted terrain (Boot Pack) indicated a more stable snowpack than compaction-free terrain. Terrain we skied and ski compacted had more intermediate and variable ECT scores.

Determining snowpack stability in compacted terrain is dependent on many factors including the type of compaction (skier, explosives, boot packed, etc.) and the density of the compaction (i.e. a single skier track versus a heavily-used snowmobile compacted slope). As well, snowpack stability tests have been validated in compaction-free terrain. Determining the effectiveness of snowpack stability tests in compacted terrain is suggested as an area for future study.

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