BOOT PACKING and "SYSTEMATIC APPLICATION OF EXPLOSIVES": SHEAR PLANE DISRUPTION TECHNIQUE IN THE CONTINENTAL CLIMATE

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ABSTRACT: Ski areas have long practiced avalanche risk reduction in order to provide continual skiing opportunities to guests in avalanche terrain, which differs from the backcountry practice of avalanche terrain avoidance during periods of poor stability. This paper explores the relationship between early season boot packing or "Systematic Application of Explosives" (SAE) and shear plane disruption or limitation in a ski area setting in the Colorado Rockies. Alternatives to boot packing, particularly the use of 1kg cast explosives in a 10 x10 meter grid (SAE), are presented. Shear plane disruption is stressed as the primary goal of boot packing, SAE, or ski compaction, and is presented in this paper as an effective method of avalanche risk reduction. Rationales based on the literature are cited. Follow up methods to ensure continual shear plane disruption with each storm throughout the season are discussed. An experiment designed to evaluate the snow strengthening effect of explosives used for the SAE disruption technique is presented. Twenty years of results clearly indicate interference with the 10+ year natural avalanche cycle; the empirical evidence supports the contention that shear plane disruption is an effective method of avalanche risk reduction.

KEYWORDS: boot packing, shear plane disruption, strategic application of explosives

1. INTRODUCTION

The continental climate is known for its high elevations, cold temperatures, and low accumulation snowfalls. This generally results in a shallow, layered and faceted early season snowcover, and in persistent weaknesses in the undisturbed snowcover throughout the season. While faceted snow is widely considered problematic, it is the layering of the snowcover, with its inherent cohesion issues, that is seen as the primary cause of avalanching. This paper does not address fracture mechanics, or grain shape or size, but rather takes a simplistic view of the primary cause of avalanching and discusses risk reduction techniques applied in the ski area. These techniques were applied at the Aspen Highlands Ski Area, located in the Elk Mountains of central Colorado at latitude ~39.9 degrees N, longitude ~106.5 degrees W and ranging in elevation from 3775m to 2440m Height Above Mean Sea Level (HASL).

In the continental climate regions, ski areas face the problem of potential avalanching in their steep terrain, especially during the early season. Given the limited season, ski areas can ill afford to keep terrain closed for extended periods.

The problem is clear and immediate; take a relatively shallow, layered snowcover that may or may not be initially cohesive, put it on an incline of 30-40 degrees, add loading in the form of new storm layers and/or unmanageable skiers and attempt to avoid avalanching both initially and throughout the ski season.

It is the task of snow safety personnel to reduce avalanche risk sufficiently to safely open avalanche terrain to skiers, both initially and during storm periods. This is generally accomplished by manipulating the snowcover in a variety of ways in order to test and improve its stability.

The goal of snowcover manipulation using any method is improved stability.

This may be accomplished by:

1. destratification (destruction of layer boundaries and thus shear planes)
2. compaction (adding strength to the snowcover if strength is defined as resistance to deformation)

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Put another way, destratification eliminates propagation pathways, and compaction increases fracture toughness.

This paper primarily discusses the risk reduction technique of shear plane disruption, with emphasis on early season skier access and examines both a primary disruption technique, boot packing, and an alternative method, Systematic Application of Explosives (SAE). An experiment designed to evaluate the snow strengthening effect of explosives used for the SAE disruption technique is presented.

These techniques are applied to a dry snowcover and results are discussed for dry snow. During spring warm up, standard wet snow forecasting technique and risk reduction methods are applied at AH and no special claim is made for improved wet snow stability using these techniques, although it is possible that wet snow stability may be increased in destratified or compacted snowcovers.

2. METHOD: BOOT PACKING

Consider this very simplistic model of avalanching:

Snow generally falls in discrete storms, thus creating layers. Layers are not always cohesive at their interfaces. Under the right conditions (i.e. loading) the cohesion between layers may fail and avalanching can result.

To reduce the risk of avalanching, one could increase interlayer cohesion OR disrupt or destroy the interlayer boundaries.

The author suggests that the primary mechanism which reduces the risk of avalanching is disruption of layer interfaces, also known as shear planes or propagation pathways.

At Aspen Highlands (AH) a ski and boot packing compaction program began 20+ years ago. It developed over the years in both size and sophistication and now it is quite comprehensive, as well as expensive. We attempt to pack virtually all our steep terrain prior to opening, using both paid staff and volunteers working for a pass. Approximately 4500 man hours are necessary to complete the job and of course that varies with weather and snowcover properties.

Over time a specific method of boot packing has been developed for use at AH. The basics include packing in the downhill direction, penetrating full depth to the ground with each step (80% compliance would be considered sufficient), creating a 1 meter x 1 meter grid with the tracks, and packing each slope completely, slopewide and top to bottom. It is thought that, as with any endeavor, problems can and will arise at the margins, so full coverage is stressed.

Safety precautions include pre-packing stability evaluation and testing, and a rope and harness belay system for use by packers when necessary.

The goal in boot packing is to thoroughly disrupt and mix all layers of the snowcover in order to eliminate fracture propagation pathways, and to add strength through compaction and densification.

A thorough follow up of explosive risk reduction, skiing or packing is necessary after each weather event and will be discussed elsewhere in this paper.

3. RESULTS: BOOT PACKING

Boot packing has been successful at AH during its 20+ year use as a risk reduction method. With close supervision and alternative methods for addressing hard slab, 80 % compliance or better on penetrating all layers is generally achieved. A review of avalanche occurrence records (AH 2008) and personal observation indicate no avalanches initiating in or penetrating into dry boot packed layers since 1988. Certainly the key here is the affecting of all layers. Early boot packing access to the terrain is critical to full penetration and the optimum settled snow depth for boot packing is about 0.5meters. At depths greater than 1 meter compliance is more difficult, and alternative methods are used.

When first begun, boot packing was thought to strengthen the snowcover and thus prevent avalanching by influencing the strength vs. stress balance. Over the years many snowpits have been dug in boot packed terrain, and while boot tracks are readily found throughout the ski season, and while they demonstrate densities generally twice that of adjacent snow, it is unlikely that these tracks are adding sufficient strength to support large loads. Figure 5, a June photograph, is included to show the persistence of boot tracks throughout the season. It is interesting to note that while surrounding grains will readily metamorphose into 5mm cupped grains and demonstrate lingering low densities, the boot-tracked grains will generally be more resistant to change, and rarely grow larger than 2-3mm. This is likely due to smaller initial grain size from the crushing action of boot packing and to the diminished pore space in the boot track. These boot tracks are obviously located beneath the boot entry point and are generally extending 0.2 m or less up from the ground, yet the positive effect of packing is maintained throughout the entire packed snowcover. Studies (Hartman 2003) indicate that at the surface, boot packed snowcovers will readily facet due to increased snow-air interfaces, and may show a loss of overall strength initially, then show a gain in strength to approximately six times that of the natural snowcover. Additionally, consider that even in a well packed area, boot tracks are spaced in a 1m x 1m grid and are directly affecting just 60% of the total surface area.

Boot packed terrain has been able to support new loads of 100+mm SWE immediately after work was done, and could likely support a greater load without failure. Experience and observations suggest that the primary mechanism for boot packed terrain avalanche reduction is shear plane disruption with added strength playing a secondary role.

Preseason boot packing may not always go smoothly. Problems that may be encountered include: inability to achieve full penetration due to snowcover hardness or depth, timing and sequence challenges, risk, and packer availability.

When these problems arise, alternative shear plane disruption solutions must be utilized. Traditional alternatives include machine packing, explosive testing and opening to guests, and very early skiing access.

A recently developed alternative is the "systematic application of explosives in a grid like pattern" also known as SAE.

4. METHOD: SAE

SAE is merely an extension of the old "saturation bombing" technique, initially used at AH on impenetrable hard slab discovered during boot packing. It seemed to be an effective way of testing and disrupting the hard slab, as well as adding some strength to the snowcover.

It followed that when confronted with a large, unpacked slope, this method, when refined, might be effective. Several steps were involved in the refinement of the technique beginning with sound reasoning based on the literature and experience.

Interpreting freely from the literature (Gubler, 1978, 1991), (Fohn, 1986) the following justification was developed:

If avalanches initiate with triggering in superweak or imperfection zones,
and the failure area must reach a size of 100m2 to generate a self propagating fracture which may result in slab release,
Then… if one can either destroy or interfere with the imperfections or disrupt, destroy or interfere with the shear plane or reduce the shear plane areas to under 100m2, then one may be successful in reducing avalanche risk.

SAE is a technique primarily addressed at reducing shear plane areas to under 100m2. The SAE technique consists of a sequential placement of 1 kilogram pentolite cast explosives on the snowcover in a 10 meter x 10 meter grid, slopewide and top to bottom. The result of this application is a roughly 10 x 10 meter grid of 1 meter radius craters across the entire slope and, as in boot packing, full coverage is stressed. It is thought that the craters have a sufficient disrupting effect up to 2 meters deep. These craters are thought to create hardened pillars of deformation resistant snow that will maintain their integrity for several months and possibly longer. (A photo of springtime snowcover ablation reveals explosive craters from throughout the entire season, included as Figure 8) This grid size appears to sufficiently limit shear plane areas to under the critical 100m2 size from the snow surface to the ground.

One of the goals of SAE is to create pillars of hardened snow which will act as barriers to fracture propagation pathways, thus limiting shear plane areas to less than the critical size needed for self propagating fracture.

Additionally, the literature (Gubler 1978, 1991) suggests that a slope can be deemed stable if tested over the entire slope with explosives placed closely enough to cover the area with 300 Pascal pressure waves
The literature (Fohn 1986; Gubler 1991) also suggests that a grid of 1 kg pentolite charges on the snow of 10 x 10 m size will cover the area targeted with more than sufficient pressure (~3000 Pa).

Explosives may initially weaken, and then strengthen the slope with time due to bond destruction and reformation. Therefore a 24 hour waiting period is observed before the next step of the SAE process is begun. The next step is to apply a large 15-30 kilogram ANFO explosive charge to the slope to redundantly test for instability. Another 24 hour waiting period is then observed.

If a slope has been thoroughly tested, it stands to reason that it can be safely skied (excepting residual risk). Skiing is a recognized method of slope stabilization, combining shear plane disruption (to the level of penetration) and strengthening through compaction. Thus skiing is the final step in the SAE method.

SAE is a mixed method involving a four tiered interaction with the snow: shear plane area limitation, explosive strengthening, thorough testing, and early access skiing compaction combined with layer boundary destruction.

5. RESULTS: SAE

The SAE technique has been practiced at AH beginning in 2004, and used three of the last four ski seasons. The technique was used in limited terrain when boot packing was not practicable. This terrain was steep, gullied alpine terrain, E to N facing, at altitudes ranging from 3775m to 3350m HASL, with an average slope angle of 40 degrees. Ground cover was predominantly broken rock. Area prepared by this technique ranged from 10 - 20 hectares, compared to approximately 60 hectares boot packed. Again, a review of avalanche occurrence records (AH 2008) and personal observation indicate no avalanches initiating in or penetrating into SAE prepared layers during this period. SAE prepared terrain has been able to support new loads of 60+mm SWE soon after work was done, and could likely support a greater load without failure. Additionally, this past season, 2007-08 brought snowfalls approaching 160% of the 30 year average and snow cover depths of up to 3+ m with average densities of 300kg/m3 were measured across both SAE prepared and boot packed terrain in the alpine.

While this paper does not address grain shape or size, it is interesting to note that a facet dominated snowcover is very common, and surface facets are a common grain shape at failure planes in the Colorado Rocky Mountains. Although SAE was developed as a replacement alternative to boot packing, the evidence suggests that a different mechanism of avalanche reduction from boot packing is operational in this case. Limiting of contiguous shear plane area through localized explosive deformation, hardening and strengthening (i.e. cratering) may be the primary active deterrent to avalanche release.

6. METHOD: EXPLOSIVE EXPERIMENT

It is recognized through experience and our own original work at AH that explosives not only test for instability but also significantly strengthen the portions of the snowcover which are cratered. In order to further investigate this hypothesis, an experiment was devised using 1 kilogram cast explosives, a ram penetrometer, a camera, and standard snowpit tools. Utilizing an open, uncompacted east facing slope, at elevation 3180m HASL, with a 30 degree slope angle, four 1kg cast explosives were detonated sequentially in a vertical line with 10 meters separation between them.

On Day 0 a ram transect was performed horizontally across explosive Crater #1. This and subsequent transects were executed at 1 meter intervals with the center of the crater at Ram # 5, 6, or 7, and a total of 11 penetrometer tests made up each transect. The second transect was done on explosive Crater #2 on Day 13. The third transect was done on Crater #3 on Day 24, and the final transect was done on Crater #4 on Day 41.

Additionally, each crater was dug out after the transect was completed and densities were taken 40cm above the ground at the crater and extending away from the crater in 1 m increments. Full data snow profiles were taken at Ram #1 each transect day, and are not included in this report. Photos of the crater profile were taken on Day 0 and Day 13 and are included here as Figures 3 and 4.Total HS on Day 0 was 110cm, and greater subsequent snow totals on day 13, 24 and 41 were not considered significant to the experiment and were ignored.

Once all the data were collected, analysis took place in the following fashion. Each ram was normalized as to depth and the bulk ram number was then calculated. The data are presented as bar graphs of the bulk ram numbers for each transect day, collectively Figure 1. Densities at 0.4m above the ground are presented in a chart, Figure 2.

7. RESULTS: EXPLOSIVE EXPERIMENT

The conditions for this experiment were good but not ideal. The experiment was done in the early spring, and so at times the upper portion of the snowcover in this area was moist, but never became entirely isothermal, although on Day 24 the snowcover did approach 0 degrees C. It would also have been preferable to work at a higher elevation in the alpine. However, results of the experiment are considered valid as conditions were consistent for each set of transects. Day 0 transects showed no significant difference in the crater area or density at the crater as expected.

The transects clearly show a significant strengthening of the snow at the crater after Day 0 and lasting throughout the experiment's time frame, if snow strength is defined as a resistance to deformation. Rather than a Ram number spike at the crater, it was thought the explosive might extend its influence out to another meter or more, creating a bit of a bell shaped graph, but that was not the case.

Densities were higher at the crater as expected, and at 1 meter away from the crater were also a bit higher than those further away. On Day 13, 24, and 41 it was difficult to obtain a density sample at the crater as the snow was quite hard.

The photos from Day 0 and Day 13 readily show a disturbance of layering at the crater. The evidence suggests that explosives have a strengthening influence locally of approximately five times in the snowcover and readily disrupt layering out to a radius of 1-1.25 meters for a period of at least 41 days.

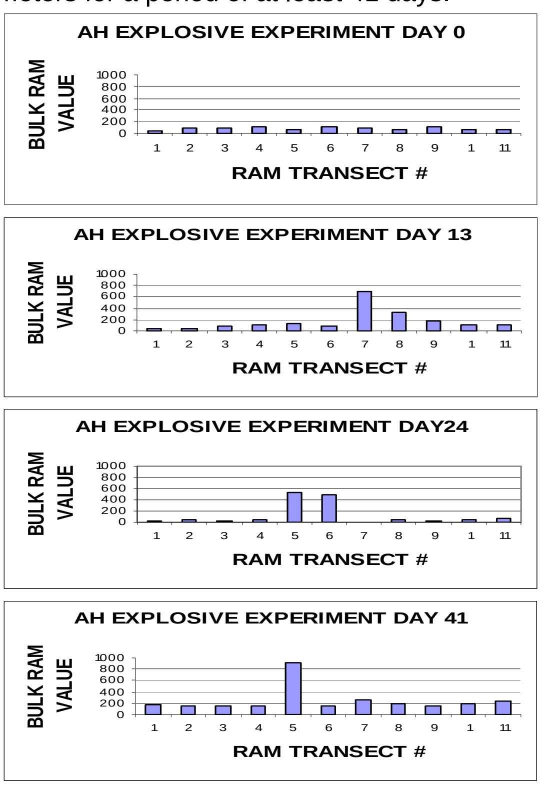

Figure 1. Explosive Experiment Ram Transect Graphs

Density Chart AH Explosive Experiment
Density (kg/m3)

	Crater	1 meter	2 meters	3 meters	4 meters
Day 0	320	360	330	310	310
Day 13	510	400	310	310	300
Day 24	500	470	370	270	270
Day 41	380	310	310	370	

Figure 2. Explosive Experiment Density Data

8. DISCUSSION

Once a slope is open for the season, follow up to any method is fairly straightforward: regular avalanche control work using explosives and ski cutting with a strong emphasis on random shot placements in space and over time, continual skiing with each storm layer to thoroughly mix every layer as it falls frequent snowpits, test, trench and full, looking for contiguous shear planes, and regular large explosive tests irrespective of storms, preferably a series across the terrain at forecaster determined intervals using a minimum of 15 kilograms ANFO for each shot.

The goal is to get skiers onto avalanche terrain as soon as possible, and to keep them on there. Skiers provide shear plane disruption and compaction subsequent to the initial work of boot packing or SAE and are the key component to a successful season long risk reduction program. Not addressed here is the problem of an impenetrable wind layer deposited by a storm or wind event during the ski season. That difficult scenario has alternate solutions as well in a layer disruption based risk reduction program.

When analyzing boot packing, several things are evident. The snow is thoroughly disturbed. Walking down slopes gives one a "feel" for the snowcover unavailable any other way. Information on ground cover, stability, and snow stratigraphy is available first hand in real time. Direct experience of disruption is very real. The snow surface is so disturbed that it is unlikely that the next storm layer will form a shear plane. This is true both for boot packed and SAE prepared terrain and is considered an important component of both methods. This next storm layer is critical, and must be disrupted and compacted by skiers as soon as possible in order to continue the disruption of layering cycle. Again, as long as packers have penetrated every layer, all fracture propagation pathways in the snowcover are thought to have been thoroughly disrupted.

Questions come to mind. Can disrupted shear planes re-form through metamorphism? Can a shear fracture propagate through snow with no pathway? There are no definitive answers, but the evidence implies a low probability of these events occurring.
Can a propagation pathway be defined as something other than a shear plane or layer boundary?

When analyzing SAE things are not as clear cut. While it is thought that the active deterrent to avalanching is shear plane area limitation, this may not be the case. The act of applying the explosive grid tests the slope so thoroughly that it is possible the active deterrent is a very stable snowcover. Early season continental snowcovers are not generally considered strong, and strong does not equate to stable, nor does weak equate to unstable. This implies that layer cohesion is the prominent factor in early season snowcover stability.

Cohesion may be conditional and may vary inversely with load, which may be linked to later deep slab instability. If layer cohesion is conditional with load and dependent on both initial conditions and later grain metamorphism, it may not be a reliable stability factor throughout the season. However the limited history demonstrates season long basal layer stability in SAE prepared terrain, suggesting that shear plane area limitation is the primary avalanche deterrent at work in the typically weak, faceted and layered snowcover to which SAE is applied

SAE method is multifaceted and it is also possible that early skiing access to stable terrain can create a compacted layer above the SAE prepared layers which is strong enough to support the skier load as well as the subsequent seasonal snow load. This, while possible, is not likely. Large explosive tests applied to all prepared areas would overcome any “bridging” effect such a layer may have and exploit imperfections lower in the snowcover.

At the same time skier created compaction (strength) is a key component of ongoing stability, along with continual skier provided shear plane disruption.

While it is difficult to assemble empirical evidence which identifies shear plane limitation as the specific active avalanche deterrent at work in SAE, consider again the little empirical evidence available. The AH explosive experiment shows that a locally strengthened pillar of snow remains at the crater site for period of time, and that layering is also locally disrupted. The literature (Gubler 1991) identifies a minimum area of weak layer failure necessary to produce a self propagating crack. A gridded application of explosives of the proper dimensions will limit the size of the area which can fail without interference. In its so far limited application, SAE treated slopes have not experienced any avalanching. More study of this method is needed, but the empirical evidence accumulated so far leads the author to conclude that shear plane limitation is the active avalanche deterrent at work.

Overall, SAE is a mixed method whose components all contribute to season long stability in SAE prepared terrain.

A comparision of avalanche occurrence records (AH 2008) from the 10 year period prior to the beginning of boot packing in the alpine clearly indicates interference with the 10+ year avalanche cycle in the alpine terrain at AH. As a typical example, 10 medium or large avalanches were documented during the five ski seasons from 1993-1997 from December through March in the avalanche path B Zero. These records are from a period before this area was an open part of the ski area. After opening and boot packing or SAE preparing B Zero no avalanches of the same sizes were recorded during the same months during the 2003-2007 seasons. Similarly, after SAE treatment in the slide paths B2 and B3, no medium or large avalanches were recorded during the three seasons for which records are available, while during the typical three year period 1993-1995, ten medium or large avalanches occurred according to the records (AH 2008).

The empirical evidence does seem to support the contention that shear plane disruption or limitation is an effective method of avalanche risk reduction. During the past decade alpine avalanche terrain has remained open for 99% of the ski area’s open days. While there are reports in the ski area industry of avalanches occurring in previously boot packed terrain, none have been observed at Aspen Highlands. These reports however, serve to remind us that no method is 100% successful and redundant control work, monitoring, and testing are necessary to insure the best chance for success.

9. PHOTOGRAPHS

Figure 3. AH Explosive Experiment Crater Day 0

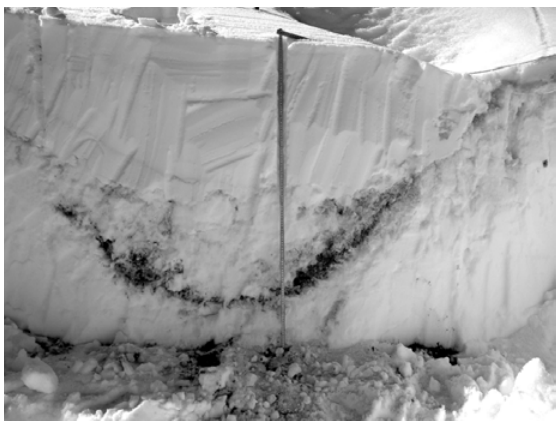

Figure 4 AH Explosive Experiment Crater Day 13

Figure 5 11/27/07 Boot tracks photographed 6/14/08

Figure 6. Boot packed terrain

Figure 7. SAE prepared terrain

Figure 8. Late season evidence of explosive craters

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