Considerations for Avalanche Hazard Reduction at Ski Areas

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Introduction
Avalanche hazard reduction at ski areas refers to the strategies and techniques used to mitigate the potential for accidents and damage resulting from the occurrence of avalanches. These operations consist of a coordinated system of forecasting, closures, testing, and active reduction of the hazard through skier compaction and avalanche release.

There are presently between 50 to 60 ski areas in the U.S with self-identified avalanche issues. About 50 of these ski areas do active hazard reduction. This operational challenge is met by balancing many factors including:
- Present limitations of avalanche science and technology
- Designing an appropriate hazard reduction scheme that is not too risky and not too conservative or impractical
- Safety of workers
- Inherent risk of post mitigation release (PMR) avalanches
- Restrictions on use of land and environmental concerns

Ski area avalanche programs have been highly successful. The risk of a skier being killed in an inbounds avalanche at a U.S. ski area is extremely rare. Despite this fact there have been 12 inbounds avalanche fatalities since 2004-2019 or slightly less than 1 per year against an average of 55,000,000 skier visits per year.

It is important to note that avalanche hazard reduction can be dangerous to the men and women that do the work. Since avalanche hazard reduction began in the U.S. in the late 1940s 56 avalanche worker deaths have occurred. 7 Patrollers have died on the job between 2008 and 2019.
Brief History of Avalanche Mitigation in the U.S.

Protection of alpine villages in Europe began centuries ago. Today you can look above the Swiss town of Davos and see the evolution of earthen, and later steel, defense structures. Hard lessons about the consequences of cutting forests above these villages were learned.

In the Austrian/Italian Alps during WWI, a new concept was learned. Greater enemy casualties could be inflicted by concentrating artillery fire on the avalanche prone slopes above enemy positions, rather than directly at them.

This lesson was not lost on pioneers of modern avalanche mitigation like Monty Atwater. Monty and Felix Koziol came to Alta at the end of WWII. Observations of avalanche behavior and the use of explosives and military weapons as a means to reduce the avalanche hazard began in earnest.

By the 60’s the technology was explored and refined. The first USFS Avalanche handbook was published and the first National Avalanche School was held. During the 70’s and 80’s most of technology in use at mitigation operations today had been identified. This time period also saw an increase in Ski Area development and a boom in winter recreation opportunities. Most of today’s major avalanche mitigation operations and Avalanche Forecast Centers developed during this period.

The period from the 90’s to today is characterized as a maturing of a successful avalanche protection industry. Evidence of industry success is that today it is highly unlikely, a person in bounds at a Ski Area (that stays out of closed areas), will be killed in an avalanche. That said, the risk of an inbounds avalanche is still present and it is not likely to be eliminated in our lifetimes.

Sharing of technology and information is a priority today as there is much still to be learned. Educating the skiing public to the risks of skiing inbounds avalanche prone terrain and the safety measures they can take has become an important part of our jobs.

Basic Elements of Avalanche Protection Planning

Snow Safety Plans contain the operational framework for avalanche protection. These plans evolve as new technology and information become available. The basic elements include:

- Authority and Mission
- Avalanche Atlas
- Forecasting System
- Data Collection
- Closures or Restricted Access
Snow Safety Plan

Below is an excerpt from the avalanche atlas of a Snow Safety Plan at Mt. Rainer N.P.

Stevens Canyon Zone III
Boundaries: Creek Chute (mp 18) to Mondo Chute
Number of Paths: 7  Aspects: SSW  Loading Directions: N, NE, E
Average Starting Zone Elevation: 5600'-5000'  Road Elevation: 3800'-3600'
Average Runnout Elevations: 3400'-3000'  Vertical Fall Distance: 2000'-2400'
Starting Zone Angle: 35-40º  Min. snow depth required to cover anchors: 1m
Ground Cover: Heather and grasses and rock outcrops
Description: This area contains 7 paths with sharply defined tracks and a wide variation in starting zone topography. These paths affect the road for 1 mile between the 3800'-3600'. This area will contain the greatest concentration of deposition from winter avalanches. The time required directly under these tracks presents the greatest potential hazard to maintenance personnel.
Spring Stability Considerations: New snow surface instability and radiation induced slides most common.
Artificial Stabilization
This method of hazard reduction is most commonly associated with protective skiing and ski compaction. Skiing a slope promotes strength in the new snow layers. It has the following benefits:

- Breaks up continuity of the shear plane
- Introduces spatial variability in the slab to inhibit fracture propagation
- May disrupt weak layer formation
- Densification of layers and acceleration of age hardening process

Moguls are a common sign of this process at work. Moguled slopes at ski areas have occasionally released when there is a deep persistent slab. Some targets for slope stabilization include:

- Early season faceting – skiing and boot packing often need to start before the area opens. Early season stabilization may require balancing the risks of letting the public ski on low snow conditions versus weak layer development that may pose a greater hazard later in the season.
- New snow instability- this is the “bread and butter mitigation” at a Ski Area. It needs to be aggressive and continuous. Temporary closures need to be short duration. Monitoring is also an important hazard forecast ingredient at a Ski Area as stabilization efforts are ineffective without sufficient traffic on the slope.
- Problem Terrain- this includes making targeted efforts in deficit zones like the shallow “facet gardens “that skiers generally avoid. Stubborn slope angles may not regularly release avalanches with typical mitigation efforts due primarily to the fact that they are not steep enough. These slopes can however build into “sleeping giants” and are great candidates for early ski stabilization.

Opening a slope to skiing should be done as soon as there is enough snow and the avalanche hazard has been reasonably reduced. This will promote the greatest overall safety of the slope through early stabilization.

Artificial Release
Perhaps the method of protection most associated with an avalanche mitigation operation is artificial release. Generally, the strategy involves balancing the timing of natural instability with operational time schedules dictated by factors like peak traffic times and ski area opening times. The most common means are by:

- Ski
- Explosive Hand charge
- Military Weapon
- Avalauncher
- GazEx
**Release by Ski**
Common at Ski Areas and involves specially trained and equipped teams. It is generally based on the principal of working from the top down. Typically, a team could follow a ridgeline and leapfrog with only one member exposed to hazard at a time. There are well-documented hazards associated with this type of activity. Hazardous conditions to avoid release by ski include:
- **Terrain**
  - Lack of escape route
  - Consequences of error
- **Snowpack**
  - Weak layer too deep
  - Hard slab conditions
- **Weather**
  - Too much snow
  - Inadequate visibility

**Use of Explosives**

Effects of Explosives
- Adds stress to snowpack
- Deformation of the snowpack
- Targeted testing for instability
- Release of avalanches
- Inhibit future avalanches

**Strategy for using Explosives**

There are some general principles that apply:
- The Right Charge
- The Right Place
- The Right Time

Photo shows deformation in the snowpack from explosive detonation.
The Right Charge

There is no “cookbook” solution to the application of explosives. Training and experience will dictate what method to use. Some techniques to consider include:

- Fast burning explosives that shock the snow to initiate brittle fracture
- Multiple charges in varied locations can increase chance of affecting the deficit zone the using fewer large charges.
- Charges may be focused to direct the energy by either aiming it (often straight down) or spreading it out (to effect a greater area)
- Charges in the air can increase peak detonation pressures
- Larger charges can be used for wet (liquid water in pore space) viscous snow

The Right Time

Timing is everything. There is often a small window of opportunity when stress and strength are closely balanced. Exploiting this window is paramount to successful mitigation attempts. One example is during a warm up when the strain rates between the weak layer and the slab are at a maximum but enough hardness remains in the slab to propagate a fracture. Some considerations:

- Too early – no results
- Too late - too much snow
  - Natural releases
  - Weak layer deeper and may be harder to affect
- Timing of natural instability
  - New loading
  - Rapid weakening
- Operational timing constraints
The Right Place
The weak layer must be affected to test or enhance the avalanche release sequence. The deeper the weak layer is the more difficult it may be to affect. In other words, the shockwave of the explosive suffers from attenuation the deeper in the snowpack it must travel.
Recognize and target deficit zones Many slide paths have chronic deficit zones. Shallow brushy or rocky areas make good facet factories. These areas can easily become buried during big storm events.
It is also important to catalog areas that are prone to surface hoar development. Surface hoar concentrations can often be found lower in paths. Large slabs extending into adjacent terrain can overlie any of these deficit zone locations. Finally, stress concentration areas need to be noted. Examples of this are steep unsupported slopes like hanging snowfields and paths broken by cliffs. Consider the following:

- What type of instability is present (persistent weak layers, new storm snow, wet snow)?
  - Can you drop a cornice or bigger load?
  - Where is the steepest part of slope?
  - Where is the wind load slope?
  - Easier to trigger shallow areas
  - Propagation from shallow to deep
  - Convex slopes
    - Immediately below steepest point
    - Are you in a safe place?
  - Concave slopes
    - Near bottom often most effective
  - Wind Rolls?
  - Low shots are often most reliable

Interpretation of Results
Some of the most valuable inputs in a mitigation operation are the results of explosive tests. After all, most stability evaluation tests are attempts to hammer the snowpack.
  - 100,000 charges are used annually at U.S. ski areas.
  - 10,000 Avalanches released (1 avalanche for every 10 charges thrown)
  - More often than not the explosive detonation does not release an avalanche

The ski industry track record with explosive testing is phenomenal. As noted above 90% of the explosive tests don’t produce avalanches. Negative results with explosives are a primary input for evaluating slope stability. However, even the most reliable tests are not perfect. Post mitigation releases are an example of residual hazard after hazard reduction
efforts have failed to produce a release. Any test should be evaluated in the context of all the other information available and the training and experience of the forecaster.

Big Open Convex slopes including the one pictured here have killed patrollers

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**Personal Safety**

There are three important steps:

- Personalize the risk
  - A common response to an accident is that we are more careful, have more experience, or better training than the victim. We need to accept that it can happen to us and then we can take the necessary steps to prevent it.

- Manage The Risk
  - This is where operational guidelines are set. This also includes limitations. For example, a guide service operating in an area covered by a Forecast Center might establish a policy that prohibits travel on any leeward slope greater than 30° when the forecast hazard is considerable. This type of mitigation trades flexibility and individual judgment in favor of a more rigid, rule-based approach.
Improve the Outcome

- This is where we as individuals seek training and take advantage of institutional knowledge to help develop our situational awareness.

The Reversible Moment

Deploying a charge in the air in an avalanche starting zone is an inherently risky maneuver and is prohibited in some operations. At a minimum a cover charge should be used before venturing out onto the slope.

In every accident there is an error chain. In each of these chains there is a moment, or moments, where that chain can be broken and the outcome reversed. Avalanche accidents, like other accidents, have common patterns. The trick is recognizing the patterns. That comes with a combination of perception, situational awareness, and experience. Unfortunately, experience by default, is often something you get just after you desperately needed it.

Situational awareness requires true multi-tasking. During a mitigation mission we are required to focus on the tasks at hand. Yet it is often events occurring on our periphery that form the error chain. We need to be aware of our mitigation results but we also need to listen carefully to our radios for other results. Even though you might be on a cold windy ridge, radiation may be having a major effect just below you. Your route partner may be
having an equipment problem. You lose visibility. These are all documented links in operational accidents. Situational awareness skills will help us see the chain develop.

**Post Mitigation Release (PMR)**

The post mitigation release is an extremely rare phenomenon where an avalanche releases after hazard reduction, often with explosives, has been completed. In some cases slopes have released up to 24 hrs. after being opened. While the mechanisms of PMR are not fully understood the releases are not caused by new snow loading or wind loading events. Since 2001 there have been 4 post mitigation releases that have resulted in skier fatalities at U.S. ski areas.

A brief summary of slap avalanche release is included here.

- Required for a slab avalanche
  - a. Crack initiation
  - b. Crack needs to grow to a critical size
  - c. Crack propagation
  - d. Overcoming friction

- Spatial variability and implications for avalanche release
  - a. Great variability looking at the slope scale
  - b. Relationship between spatial variability and slope stability
The amount of spatial variability changes depending on the specific slope, the specific characteristics of the weak layer, and the way the slab is distributed over the weak layer. This variability also changes over time.

- Spatial variability is a possible reason for post-mitigation release avalanches (PCRs)
  a. This results in crack initiation issues
  b. This results in crack and fracture propagation issues (asymmetric fracture propagation)
  c. This means some degree of uncertainty will be present even after thorough hazard reduction efforts have been employed.

Findings of asymmetric fracture propagation propensity over slopes with spatially variable slab thickness have practical implications for Explosive placement. They may be more effective when placed in area where the slab is thinner than at its thickest spot. Still, to support fracture propagation on the weak layer, a slab needs to be strong enough and therefore thick enough to withstand the energy transfer at the point of initiation (Gauthier, 2007).

Some considerations for avalanche hazard reduction and PMRs include:

- Know PMR characteristics
- Importance of ski compaction and opening terrain early
- Note Avalanche Activity
- Remember it is still Right Charge, Right Place, Right Time
- Document Results/ placement of shots
- Be suspicious when opening terrain for the first time
- Communicate the risk of inbounds avalanches to skiers!

### Characteristics of Inbounds Avalanches

<table>
<thead>
<tr>
<th>Characteristics of fatal Inbounds avalanches (13 total)</th>
<th>Expert Terrain</th>
<th>Facets involved</th>
<th>Mitigation that day</th>
<th>Opened for first time of season</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVSSR (2004-05)</td>
<td>NA</td>
<td>UNK</td>
<td>No</td>
<td>Kid fell from lift into avalanche</td>
</tr>
<tr>
<td>A. Basin (2004-05)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Spring Wet Slab</td>
</tr>
<tr>
<td>Canyons (2007-08) Litigation (Defense verdict)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Snowbird (2008-09)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Location</td>
<td>Litigation</td>
<td>Open</td>
<td>Days Prior</td>
<td>Unskiable Until</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------</td>
<td>------</td>
<td>------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Squaw Valley (2008-09)</td>
<td>Yes</td>
<td>UNK</td>
<td>Yes</td>
<td>No (but very recently)</td>
</tr>
<tr>
<td>Jackson Hole (2008-09)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sun Valley (2009-10)</td>
<td>Yes</td>
<td>Yes</td>
<td>2 days prior</td>
<td>Unskiable until 2 days prior</td>
</tr>
<tr>
<td>Vail (2011-12)</td>
<td>Yes</td>
<td>Yes</td>
<td>UNK</td>
<td>Not opened yet</td>
</tr>
<tr>
<td>Winter Park (2011-12)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>UNK</td>
</tr>
<tr>
<td>Donner Ski Ranch (2012-13)</td>
<td>Yes</td>
<td>UNK</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Mt Rose (2017)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Not opened yet</td>
</tr>
<tr>
<td>Taos (2019) 2 Fatalites</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>First opened with lift access 2 days prior</td>
</tr>
</tbody>
</table>

Considerations for explosive Use include:
- Persistent weak layers and Deep slab instability
  - Vary placements
  - Use of more charges or larger charges as appropriate
  - Rely on training and experience and institutional knowledge
- Wet snow
  - Larger charges
  - Timing
- Charges on or above snow surface as appropriate

**Decisions to open avalanche slopes at ski areas will have some degree uncertainty due to the inherent residual risk even after thorough avalanche hazard mitigation has been done. This uncertainty cannot be eliminated and the risk is integral to the sport of skiing. Decisions to open avalanche terrain should not be too risky but also should not be too conservative.**
Communicating the Risk of inbounds avalanche hazard

- Compartmentalization of avalanche areas with rope lines - enter thru gates only
- Signage that addresses avalanche hazard when open
- Education of skiers when opening gates
- A system of warning that coordinates with trail maps and other sources of information

Trail map with avalanche prone areas shaded and a corresponding shaded box describing the inbounds avalanche risk.
The risks presented by snow at ski areas are not limited to in bounds avalanches. There are increased risks to skiers from snow immersion (SIS) while skiing off of groomed trails. The risk is elevated when powder skiing in steep treed areas particularly where there has been 2 feet or more of new snow. Skiers can be educated about this hazard through signage, brochures and ski area safety web pages.

Another hazard is encountered when skiers exit the designated ski area boundary. The ski area boundary should be clearly designated with exit points. Ski areas can also educate skiers about these risks and support local training programs that cover backcountry hazards.