AN EXPERIMENTAL DYNAMIC RESPONSE STUDY OF HARD SLAB SEASONAL SNOW TO EXPLOSIVE AVALANCHE HAZARD MITIGATION

Josephine Bones,*[1] Daniel Miller[1] Scotty Savage[2]
[1]Department of Civil Engineering Montana State University, Bozeman, MT
[2]Friends of the Gallatin National Forest Avalanche Center, Bozeman, MT

Abstract: Avalanche hazard mitigation programs routinely use explosive charges to release avalanches and test slope stability, but fundamental understanding of snowpack response to explosive detonations is lacking. This project, conducted in southwest Montana, aimed to verify past findings and further develop an understanding of snow explosive interactions, particularly for hard slab conditions. Hard slab snow poses challenges for operational avalanche programs. Past research collected dynamic snow responses 10-100m from the detonation site while the current study placed an instrumentation suite within 3-7m of the detonation. Pentolite cast boosters (0.9kg) were detonated at 0.0m, 0.5m, 1.0m, 1.5m, and 2.0m heights above the hard slab snow surface. An array of six orthogonally paired accelerometers, inserted into the snowpack at three different depths at two locations from the blast, recorded snow accelerations. High pressure sensors, located at and above the snow surface, measured air overpressures. Distances, radial and horizontal, from the explosives and charge height were scaled to TNT equivalents to aid in explosive placement comparisons. A substantial advantage was recorded in maximum snow accelerations due to elevating the explosive above the snow surface. Vertical and radial attenuation rates within the snowpack were determined. The data shows suspending charges not only increases overall response, but also increases the effective range and depth with no penalty in shock attenuation. The avalanche community benefits from this research by an advancement in understanding snow explosive interactions thereby potentially increasing avalanche programs' safety and efficiency.

1. INTRODUCTION

Snow stability presents a major and widespread concern during winter for ski area personnel and State Departments of Transportation. Avalanche hazards associated with mountain roads and ski areas often are mitigated utilizing explosives. Maximizing the range and snow depth impacted by the explosive is essential to increasing the probability of success. Use of explosives for avalanche mitigation generally results in successful outcomes, but occasionally the snowpack has responded unexpectedly. Recently, there have been several unintended avalanche releases following explosive mitigation work at ski areas in the US (Abromeit, 2010). The unintended avalanches occurring following mitigation measures are commonly referred to as post-control releases and reinforce the need for continued and expanded research into the interactions between snow and explosives. Hard slab conditions are frequently associated with post-control releases and incidents involving avalanche professionals.

*Corresponding author address: Josephine Bones, Montana State University, Bozeman, MT, USA 59715; tel: 406-212-4520; fax: 406-992-6105; email: jodiebones@gmail.com+

Previous studies to investigate snowpack explosive interactions, utilizing field measurements, primarily were conducted at large distances from the blast center. A study conducted in Switzerland in the 1970's, considered charge mass, snowpack stratigraphy, explosive type, charge placement relative to the surface, explosive type and ground type (Gubler, 1977). Accelerometers were used at various locations in the snowpack to measure snow dynamic responses. The majority of data collected was 10-60m radially from the charge detonation location. A significant result from this research was that 1 kg charges detonated from 1 -2 m above the surface result in larger snowpack responses thus increasing the effectiveness of explosives for releasing avalanches. Another study used mining seismographs to measure the vertical movement of snow during explosive events (Ueland, 1992). This work confirmed Gubler's air blast advantage over surface or buried charges. Ueland also examined shock attenuation through the snowpack depth. A primary dependence for attenuation rates was found to be snow hardness. Ueland found hard snowpacks allowed for deeper penetration of stress waves than softer snow. The mining seismographs Ueland used could not be closer than 20m from the blast center.

An earlier phase of this project focused on soft slab snow response to explosive detonations (Bones et al, 2012). While testing locations were different, the methodologies for soft slab investigations were similar to those presented here for hard slab snow conditions.

2. METHODOLOGY

This research project focuses on measuring the dynamic response of snow within close proximity to the explosive in hard slab snow conditions. The experimental goals of this study include: 1) develop a instrumentation suite that is field portable and capable of capturing snow dynamic response and air blast overpressure, 2) measure the effect of explosive placement relative to the snow surface 3) measure the effect of depth and range from the blast on snowpack response, 4) measure the shock attenuation through the snowpack depth and range 5) investigate test repeatability. The gathered information will be compared to findings from previously mentioned similar projects.

This project was field based. A suitable test site was identified, proper instrumentation was placed, and explosive charges were detonated. An instrumentation array was inserted in the snowpack to record acceleration of the snowpack. Pressure sensors were installed on and 1.5m above the snow surface. Single 0.9 kg Pentolite cast boosters were detonated at 0.0m, 0.5m, 1.0m, 1.5m, and 2.0m above the snowpack. A high speed data collection system was used to record the snow accelerations and air overpressures as a result of the charge detonation.

2.1 *Location*

The project started in the 2009-10 winter, it has continued through the winter of 2011-12. In past seasons, the research focused on soft slab responses (Bones et al, 2012) while in 2011-12 the research concentrated on hard slab snow conditions. Field measurements reported here were taken winter 2011-12 at Big Sky Resort, Montana. Big Sky Ski Patrol personnel partnered in this portion of the research and performed all explosive handling. A lack of adequate snow depth and hard slabs for a large portion of the season resulted in testing occurring during the later part of the season when the upper portion of the snowpack was damp. Multiple locations at Big Sky Resort were used. The locations were chosen with area personnel helping locate suitable unskied hard slab conditions. Three different locations were used, conducting tests at only one site on a given day. The areas were large enough to conduct multiple tests each day. All areas consisted of low angle slopes that would not release due to explosive use. While the sites were not located in avalanche terrain, they provided an excellent opportunity to measure hard slab snow explosive interactions over multiple tests.

2.2 *Instrumentation*

The instrumentation suite was required to record snow acceleration and air blast pressures in close proximity to the charge. Snow dynamic responses were measured utilizing dual-axis capacitive accelerometers. These accelerometers were inserted into the snow cover at three distinct depths and two radial distances referenced to the explosive charge location. The dual-axis accelerometers permitted vertical and radial responses to be recorded for a single location. Air blast pressures were measured using two high pressure acoustic sensors placed at a specific radial distance at two vertical elevations.

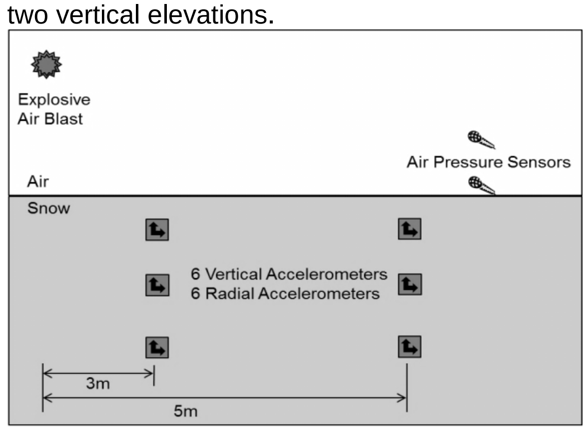

Figure 1: Typical test set up with accelerometers at two radial distances, three snow depths, and two air pressure sensors.

Two accelerometer types were utilized to meet dynamic range requirements at two locations. The specific accelerometers were sized based on responses from the previous winter season. At 3m from the blast, the accelerometer array consisted of Analog Devices ADXL 278 ±70/±35g dual-axis accelerometers. The 70g axis was aligned vertically and the 35g axis was aligned radially outward from the blast. The accelerometers placed 5m from the blast were

Analog Devices ADXL321 ±18g dual axis-accelerometers. Both types of accelerometers were mounted on evaluation boards then conformably coated in epoxy for moisture protection. The accelerometers were very small and the amount of epoxy used was minimized to reduce the possibility of introducing a snow accelerometer mechanical impedance mismatch.

The accelerometers were placed in the snowpack by digging a small pit and inserting the accelerometer cards into the pit face. The pit wall was oriented away from the blast and the accelerometers were placed in undisturbed snow. Prior to testing the pit was completely backfilled. The accelerometer depth placements were determined by the snowpack conditions for each particular test day, but were placed in similar locations for all tests. Average depths, referenced from the snow surface, were 0.22m, 0.53m, and 0.81m respectively. The array of six paired accelerometers (three each vertical and radial) were placed at two radial distances (3m and 5m, Figure 1) from the blast center.

Two prototype Larcor acoustic instruments (±34.4 kPa) were used to measure blast overpressure just above the surface and at an elevated location at a single radial distance. These custom sensors were designed specifically for high pressure operations. The predicted maximum overpressure and the sensor’s range determined the placement distance originally of 5 m from the explosive. The range was increased to 7m after saturating the sensors at the 5m placement. The usable microphone frequency range was 2 - 1000 Hz.

The sensor signals were transmitted to a National Instruments NI cDAQ-9188 Instruments Data Acquisition System module (DAQ). A notebook computer was utilized in conjunction with the DAQ to record transducer signals. The specific DAQ was chosen based on its ability to sample multiple data channels very rapidly. To address the sampling requirements, a National Instruments Labview v8.6 code was generated using TDMS (technical data management streaming), a data capture format that enabled data acquisition sampling rates of 25 kHz per channel was used during test sequences. Using Nyquist theorem sampling rate considerations, the sampling rate was determined to be adequate to capture the transient and relatively high-frequency acceleration signal components and sufficient to monitor acoustic signals well beyond the range of the microphone.

2.3 *Daily test protocol*

Upon arrival to a test location, individual test sites were selected. Sites were chosen to ensure a minimum of 0.9m of hard slab depth at the charge location and 10m between blast centers. A snow pit was excavated on each test day to determine the snow stratigraphy, density and depth. All charges were 0.9kg Pentolite cast boosters. Charge elevations ranged from the surface to 2m above the snow surface at 0.5m increments. The suspended charges were placed on bamboo shafts, a standard in the industry. All charges were orientated vertically and taped to the bamboo shaft. Snowpack dynamic response and air blast pressure data were collected using the instrumentation suite. A total of 19 tests were taken and are summarized in Table 1.

Table 1: Field testing matrix showing all tests. Fourteen blast response tests were conducted as well as five identical tests conducted on the same day to demonstrate repeatability.

Charge elevation above the snow surface	Blast response tests	Repeat test
0m	3	
0.5m	3	
1m	3	5
1.5m	3	
2m	2	

3. DATA PROCESSING

The focus of this research is on acceleration measurements and trends pertaining to these values. Data was also gathered by the pressure sensors, but is not presented here. The acceleration data was analyzed for trends in charge placement, range and depth of influence, vertical and radial shock attenuation rates within the snow cover, and the repeatability of tests. Raw accelerometer voltage data was converted to acceleration in units of g’s and m/s^2. Acceleration magnitudes were determined with the radial and vertical accelerometer readings as acceleration vector components, and the average maximum acceleration magnitudes were analyzed. An example of resultant acceleration time response is shown in Figure 2. The maximum resultant magnitude is used from each test for a comparison of effectiveness. Decay in peak magnitude with range is evident as is the time delay for shock travel between sensor locations.

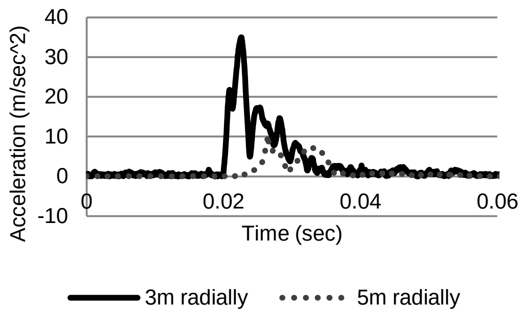

Figure 2: Example resultant acceleration magnitude data 3m and 5m radially from the charge. The resultant acceleration is the vector magnitude comprised of the vertical and radial acceleration components. Each data series is the acceleration magnitude of a single dual axis accelerometer experienced.

To allow comparison of different distances, equivalent scaled distances and blast heights were calculated, referenced to a 1 kg (2.2 lb) TNT detonation. The scaled distance relationship used here is (Kinney and Graham, 1985):

(1) $L_s=L_a/m^{1/3}$.

Where L_s is the TNT equivalent scaled distance ($m/kg^{1/3}$), L_a is the actual distance (m), and m is the TNT equivalent charge mass (kg). This scaling was applied to the charge height above the snowpack, the distance from the charge center, and the depth of sensors below the snow surface.

4. DISCUSSION OF RESULTS

4.1 *Impact of Charge Placement*

Data from the accelerometers was examined to determine the relationship between charge height above the snow and the dynamic response of the snow cover. For each charge elevation, an average peak response and average scaled depth of the sensors were determined. The average response resulted from an average of the maximum responses recorded during each test. These average responses at varying snow depths and either 3m or 5m from the charge radially were examined in relation to the various charge heights. The 3m radial distance data is presented in Figure 3.

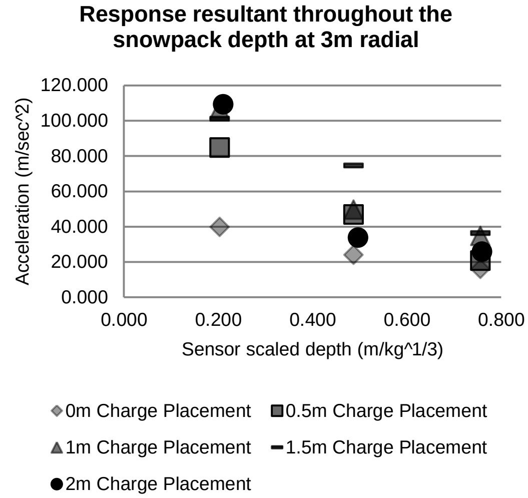

Figure 3: Average peak acceleration responses 3m radially from the charge center verses scaled sensor depths for various charge heights.

Figure 3 illustrates a significant advantage due to raising the explosive off the snow surface, particularly within the upper layers of the snowpack. This is in agreement with Gubler's (1977) results pertaining to charge height. The advantage of raising the charge varies slightly for different depths within the snowpack and different radial distances. The surface charge consistently resulted in the smallest response. All sensor recordings show a significant increase in maximum acceleration due to elevating the explosive above the snow surface as shown in Table 2. The advantage was more pronounced closer to the charge, either radially from the charge or vertically within the snowpack. While the overall response was appreciably less 5m from the explosive, the advantageous trend was found to be similar as at 3m. The acceleration increases are not as large, but still are significant when compared to surface blast responses.

Table 2: Percent increase in peak acceleration compared to a surface charge. Top, middle, and bottom refer to the general depth location of accelerometers.

Charge	3m Radially			5m Radially		
Elevation	Top	Middle	Bottom	Top	Middle	Bottom
0m	0	0	0	0	0	0
0.5m	68	96	29	35	43	70
1m	111	108	117	55	10	58
1.5m	101	212	128	30	17	30
2m	117	41	62	84	48	61

Continuing to raise the charge would eventually result in a degraded response as geometric wave expansion exceeds the suspended charge advantage. The maximum elevation for a 0.9kg Pentolite cast primer is believed to be approximately 2m above the snowpack, but responses were not investigated above this height. Figure 4 shows the significant acceleration increase when the explosive is suspended.

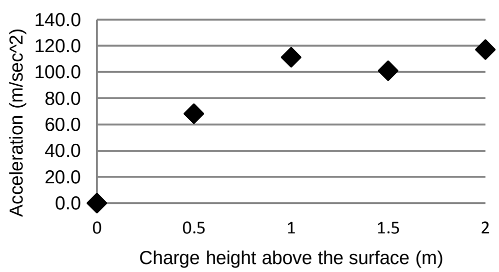

Figure 4: Percent increase over surface placement in average acceleration experienced in the top layer of snow for various charge heights at a distance of 3m from the explosive.

The greater the acceleration of the snowpack results in the snow experiencing greater stress (Miller et al, 2011). Being able to create greater acceleration of the snow by elevating an explosive could result in a higher probability of triggering an avalanche. Reaching the trigger point more often would potentially result in fewer unintended avalanche releases as well as using fewer charges to achieve the same result.

4.2 *Attenuation Rates*

Attenuation rates pertaining to radial range and depth were examined. For a particular depth within the snowpack, peak acceleration attenuation as a function of radial distance from the blast was analyzed. Attenuation of the shockwave occurred due to the geometric expansion of the shock wave, snow deformation and interaction with the ice/pore network as the shock moved through the snowpack. In Figure 5, an example peak acceleration response as a function of scaled distance from the blast is shown for sensors in the middle of the snowpack for a specific charge height. Curves were fit for each accelerometer sensor depths using a power function regression analysis of the form:

(2) $$a = c\, L_s^{d}$$

where a is the peak acceleration (m/s^2) magnitude, c is a power coefficient and d is the power exponent. The rate of attenuation is measured here as d.

The power exponents, d, from each of the individual tests were examined to determine the rate of radial and vertical attenuation of the shock wave and whether the attenuation exponent was dependent on the charge blast height.

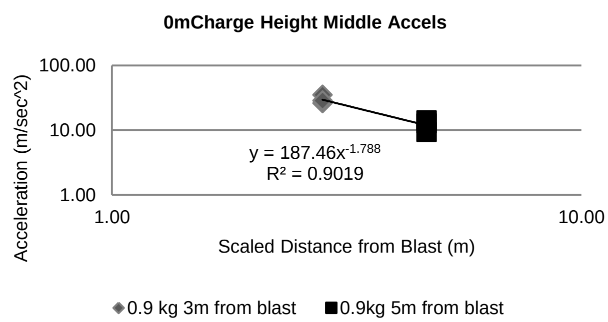

Figure 5: Acceleration magnitudes recorded at the middle snow layers for multiple charges placed on the snow surface. In this case, c=187.46 and d=-1.788.

Figure 6 is a comparison of the radial attenuation rate versus scaled charge height. The averages of the different layers are very similar to each other and averaged d=-2. This indicates the attenuation rate is largely independent of depth within the snowpack. The data also suggests the attenuation rate is generally independent of the charge elevation above the snowpack.

While the attenuation rate at the three different accelerometer depths were very similar, the middle and bottom rates were extremely close (Figure 6). This most likely reflects the difference in the snow stratigraphy. On all test days the lower portion of the snowpack was very homogeneous in respect to density and hardness.

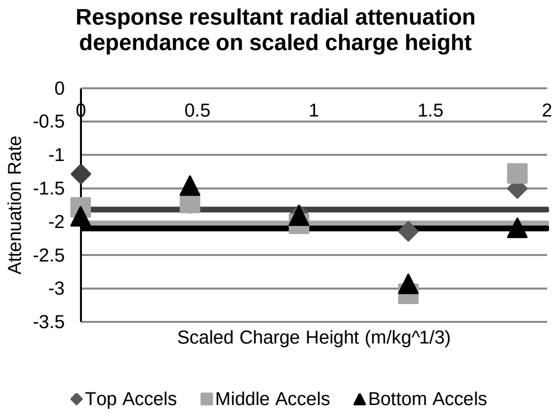

Figure 6: Radial attenuation rates (d) dependence on charge height. The horizontal lines represent the average attenuation rate for each accelerometer depth.

Attenuation through the snowpack depth was also investigated. Individual charge heights were plotted in the same fashion as radial rates. The vertical attenuation was found to be much less than radial. The vertical attenuation was primarily due to the shockwave snow interaction and less due to geometric expansion. When the exponents were shown together (Figure 7), there does not appear to be a strong correlation to the charge height. Since the averages are so similar, the attenuation rates appear to be largely independent of distance from charge. The attenuation rates at all distances other than the 1.5m elevated charge are very similar and resulted in similar averages.

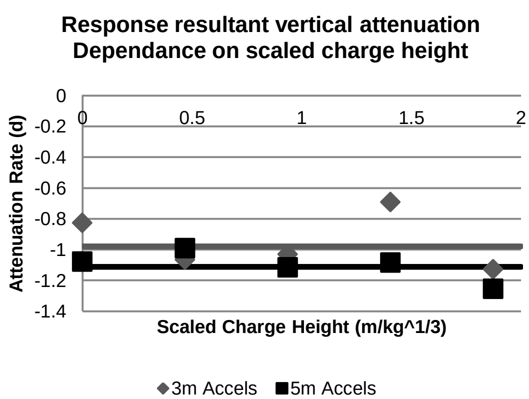

Figure 7: Vertical attenuation rate (d) versus scaled charge height with averages for the individual data series shown by solid horizontal lines.

Attenuation rate independence from charge elevation and location as well as depth is pertinent to maximizing an explosive blast's impact. It was previously determined that raising a charge from the snow surface resulted in greater acceleration of the snowpack. The combination of maximizing snowpack acceleration and minimizing shockwave attenuation is a highly desired result in avalanche mitigation work; the suspended charge will increase the potential horizontal range and depth of effect with no penalty in attenuation.

4.3 <u>*Test Repeatability*</u>
Data gathered during five repeatability tests was analyzed independently to determine attenuation rates in the radial and vertical directions. These tests were conducted to ensure a repeatable and consistent test process. The attenuation rates for this data set were found to be less than for the blast response data set. This was the case for both the radial and vertical directions. This may be attributed to the snowpack on the day the tests were performed.

Average accelerations experienced, during repeatability testing, at all accelerometer locations and the standard deviation of the data is presented in Table 3. The relatively small standard deviations imply the method being utilized to gather data is appropriate. The top layer has the largest standard deviation at both distances. This most likely is a result of differences in the newer snow and the snow that had accumulated previously.

Table 3: Average acceleration (m/sec^2) and standard deviation (m/sec^2) of data collected for repeatability testing.

	3m Radial			5m Radial		
	Top	Middle	Bottom	Top	Middle	Bottom
Average	37.1	21.9	14.5	17.5	12.3	9.3
Std dev	12.8	9.1	5.0	5.6	2.5	2.4

5. SUMMARY

Hard slab snowpack accelerations due to explosive detonations of 0.9 kg Pentolite cast primers were recorded in a field setting using a portable instrumentation array. The responses were analyzed to determine the correlation between charge elevation and acceleration recorded in the snowpack with range and depth. The results confirmed raising a charge resulted in greater acceleration of the snow. Attenuation of the shockwave radially and through the depth of the snow cover was investigated. The vertical attenuation was found to be less than the radial attenuation. In both directions it was determined the attenuation rate is independent of the charge height. It also was determined the attenuation rate does not change appreciably with range or depth. The attenuation rate findings combined with the advantage of elevating charges has an important bearing on avalanche mitigation work. Raising a charge not only results in greater dynamic response in the snowpack but an increased area of influence from the same size charge.

6. FUTURE WORK

Obtaining dry hard slab data in the future would be beneficial for comparisons to soft slab data. A majority of the soft slab data previously gathered was dry with a very small sample size of moist snow conditions. The moisture difference presents challenges when trying to compare the different slab type responses.

In the future the project is looking to model, and verify using field data, the snow response utilizing the computer program ANSYS AUTODYN. Miller et al (2011) has shown the programs ability to model the explosive event, but the model has yet to be verified. AUTODYN is well suited for modeling explosive evens involving two distinct mediums, air and snow in this case.

ACKNOWLEDGEMENTS We would like to thank the US National Avalanche Center, the National Ski Area Association, the American Avalanche Association and Sigma Xi for their financial support of this work. Thank you Big Sky ski patrol for a testing location and explosive handing.

REFERENCES

Abromeit, D., 2010. Inbounds incidents & fatalities 2008/9. Avalanche Review. 28(3), 26.

Bones, J Miller, D and Larson R., 2012, Exploring the effectiveness of explosives for avalanche control. Thirty-eighth annual conference on explosives and blasting technique. February 12-15, 2012. Nashville: International Society of Explosive Engineers. 149-158.

Gubler, H., 1977. Artificial Release of Avalanches by Explosives. Journal of Glaciology. 19(81), 419-429.

Kinney, G.F. and K.J. Graham, 1985. Explosive Shocks in Air. Springer-Verlag, Berlin Heidelberg New York Tokyo, ISBN 3-540-15147-8.

Miller, D.A., Tichota, R.G., Adams, E.E., 2011. An explicit numerical model for the stud 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. 1992 International Snow Science Workshop, Breckenridge, CO.