EXPERIMENTALLY DERIVED AFFECTED SNOW VOLUMES AND DYNAMIC RESPONSE OF HARD SLAB SNOW FROM EXPLOSIVES

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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. Past research collected dynamic snow responses 10-100m from the detonation site while the current study placed an instrumentation suite within 3-5m of the detonation. Pentolite cast boosters (0.9kg) were detonated from 0.0m to 2.0m 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. Vertical and radial attenuation functions within the snowpack were determined from accelerometer data. Using the attention functions, predictions for depth and range of affected snow were developed. While the depth of affected snow did not increase substantially with a raised explosive, the range did show significant increases yielding an 80-100% increase in the volume of snow impacted by the explosive. The data also demonstrated that there was virtually no penalty in shockwave attenuation from raising the explosive.

KEYWORDS: snow explosive response, avalanche hazard mitigation.

1. INTRODUCTION

When avalanches pose a direct threat to lives, property or transportation routes, risk is often mitigated through the use of artificial avalanche release methods. Artificial avalanche initiation is primarily done with the use of explosives (LaChapelle, 1977). Explosives for avalanche mitigation are generally effective and yield desired results, but occasionally the snowpack responds unexpectedly. In recent years, there have been several within ski area boundaries unintended avalanche releases following mitigation work. In the 2008-2009 winter season there were four fatalities and another 18 people involved in avalanches within US ski area boundaries (Abromeit, 2010). From 2009 to 2012, avalanches within resort boundaries have killed an additional five people (www.avalanche.org). Most of these incidents have been classified as post-control releases (avalanches that occur after mitigation measures have been used) and illustrate the need for continued and expanded research efforts (Ferrari, 2010).

While avalanche hazard mitigation is common, a fundamental understanding of the interactions between snow and explosives is lacking. During avalanche mitigation, practitioners use explosives to overload a weak layer in the snowpack. On sufficiently steep slopes, explosives overpressures are used to load the snowpack (Miller et al, 2011) resulting in internal structural failure and avalanches (Johnson et al, 1994, Johnson et al, 1993). The load necessary to initiate failure differs due to variability in snowpack conditions and priorities leading to variable instability (LaChapelle, 1977). To increase the probability of success, it is desired to maximize stress and volume impacted by the explosive.

There have been limited experimental research projects specifically focusing on snow's dynamic response to explosive detonations. Gubler (1977) conducted field tests to determine the effect of pressure waves due to explosive detonations in snow beyond the crater zone. Gubler used accelerometers and pressure sensors placed within the snowpack to record responses to explosive deto-

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nations. The measurements were taken 10-60 m (the majority at 20m or greater) from the detonation. Gubler noted that detonations below the snow surface resulted in the smallest dynamic response, a decrease of 1-2 orders of magnitude, when compared to surface and elevated charge placements. This response for buried detonations indicated coupling between the explosive and snow was low. From his work using 1 kg charges, Gubler determined an elevated charge height of 1-2 m would be the most effective for initiating an avalanche in dry snow conditions.

The pressure shockwave above the snow surface also was investigated in multiple studies and summarized by Mellor (1985). Using values from Ingram (1962), Joachim (1964), and Mellor and Smith (1967), Mellor determined the overpressure attenuation with radial distance. A power regression data fit indicated an attenuation exponent of -1.6. A summary of overpressure values obtained by Wisotski and Snyder (1966), again summarized by Mellor, indicated the overpressure with range was proportional to $1/r^2$ where r is the radial distance from the explosive. A comparison by Mellor of shock reflection showed the reflection to be less over snow (Ingram,1962) than a rigid surface. Using data from Wisotski and Snyder (1966), Mellor created plots indicating that regardless of the charge detonation elevation and the radial distance, the overpressure was less for snow than bare ground.

Using an explicit non-linear dynamic model, Miller et al (2011) developed a numerical model coupling the interaction between the snow and air including non-linear explosive constitutive responses of each. The model pointed to a shear wave moving with the explosive shock that may be the primary mechanism for artificial avalanche release. They also showed that the reflected shock interaction with the snow surface, due to shock wave engagement geometry, explained the enhanced response to elevated charges. This study focused on a weak layer/slab scenario but did not specifically address hard or soft slabs.

In past research efforts, the methods and technology available to record interactions between explosives and the snowpack restricted the closest measurements to be at least 10 m from the explosive. These studies did confirm the advantage of elevating charges, a common practice today. It is desired to measure snow responses through the snowpack depth and at various ranges with the goal of making measurements in closer proximity to the explosives. Technological advances allow sensor placement to be closer than in the past, resulting in quantification of the snowpack response in close proximity to the detonation. Bones et al (2012) details the tools and techniques used to gather the data for this study. The techniques will be briefly summarized here. In the current study, dynamic response data from Bones et al (2012) was analyzed to estimate the range, depth and resulting volume of affected snow during explosive events.

2. METHODOLOGY

Bones et al (2012) focused on measuring the dynamic response of snow within close proximity to the explosive in hard slab snow conditions. The experimental goals included: 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.

In summary, an instrumentation suite recorded snow acceleration and air blast pressures in close proximity to the charge. Snow dynamic responses were recorded 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 pressures were measured using two high pressure acoustic sensors placed at a specific radial distance at two vertical elevations.

Nineteen hard slab tests were conducted at Big Sky Resort located in Southwest, Montana. All tests were conducted with 0.9 kg Pentolite cast boosters. Shots were detonated from the snow surface up to 2 m elevated height. Air blasts were achieved by placing charges on bamboo.

Using the experimental data collected from hard slabs, an analysis of the dynamic response was conducted to predict the range, depth and volume of snow that experienced threshold accelerations.

Resultant acceleration magnitudes, based on the vertical and radial components, were computed. Shockwave attenuation is due to a combination of geometric expansion of the shock wave, snow deformation and interactions within the ice pore network (Mellor, 1973). 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):

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

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).Peak acceleration magnitude as a function of scaled radial distance and depth was determined. Acceleration was plotted as a function of scaled distance and fit with a power regression equation of the form:

$$A_P = cL_S{}^d. \quad (2)$$

Where A_p is the peak acceleration magnitude (m/sec^2), L_S is the scaled distance ($m/kg^{1/3}$), *c* ($kg^{1/3}/sec^2$) is a coefficient and *d* is the power exponent. Both *c* and *d* were found by curve fitting experimental data. The exponent *d* describes the attenuation of the shockwave. Since the shockwave is diminishing with distance due to wave expansion and snow attenuation, the exponent *d* is negative. The larger the magnitude of *d*, the faster the shockwave is decaying. Power law fitting of data was shown to be applicable to shockwave attenuation in snow (Gubler, 1977; Johnson et al, 1994; Solie et al, 1993). TNT scaling law allows for inclusion of different charge masses.

Using the power regression acceleration magnitude relationships (eqn 2), approximations of range and depth can be made for specific acceleration values.

3. RESULTS AND DISCUSSION

The acceleration responses were investigated to determine the effect of charge elevation on: snowpack response, the radial attenuation of the resultant acceleration response, the vertical attenuation of the resultant acceleration response and volume of snow affected. The acceleration values used are the average peak acceleration response magnitudes.

To investigate the implications on the snow acceleration due to raising an explosive above the snow surface, the percent change in the average peak resultant acceleration recorded at all accelerometer locations was determined. The surface charge was used as the baseline in calculating changes. Detonations on the snow surface resulted in the smallest snow accelerations with all other heights showing increases. The percent increase is shown in Table 1.

Table 1. Percent increase of peak acceleration resultants for elevated charges compared to surface detonations over hard slabs. Data is for 0.9 kg charges. Two radial ranges at top, middle and bottom layers.

Acceleration Percent Increase in Hard Slab Snow						
Charge Height	3 m Radially			5 m Radially		
	Top	Mid	Bot	Top	Mid	Bot
0 m	0	0	0	0	0	0
0.5 m	68	96	29	35	8	70
1 m	111	108	117	55	10	58
1.5 m	101	212	128	30	17	30
2 m	117	41	62	84	48	61

Gubler (1977) indicated the optimum height for an explosive was 1-2 m above the snowpack. Table 1 indicates for this charge elevation range, an 8% - 212% increase in average peak acceleration was measured. Raising a charge too much would eventually result in decreased acceleration response as geometric wave expansion out paces the enhancement from surface engagement geometry.

Using the peak acceleration data, attenuation was determined and compared for the different charge heights. The power exponent, *d* from eqn (2), was compared along with the corresponding charge height to examine the relationship between charge location and vertical as well as radial attenuation. In both cases, the attenuation exponent, *d*, was largely independent of charge height. For vertical attenuation, average values were at was -0.98 (3 m from the blast) and -1.11(5 m from the blast). The radial attenuation exponent was -1.45, -1.62, and -1.73 for the top, middle and bottom layers respectively.

The results of greater snowpack acceleration due to elevating the explosive and the shockwave attenuation being independent of the charge elevation reinforce the utility of elevating charges. This raises the question, what region of influence, from different placements, can be expected from explosives? This may be measured not only in range at the surface, but combined with depth to give a volume of influence. By increasing the effective depth and range of a single explosive, a higher probability of artificial avalanche release is achieved.

With the radial attenuation curves developed from the experimental data (eqn 2), the range for specific acceleration values can be found. Using the accelerometers placed at the two radial distances from the detonation, the range in the top, middle, and bottom layers for a particular acceleration of interest was predicted. These ranges, for each charge height, were fit with a linear regression through the snowpack depth. Multiple types of regression curves were explored, but linear fit the data very well. The linear regression equations were then used to determine the range, depth, and volume for the different charge elevations. A schematic of the approach is shown in Figure 1.This method allows for choosing an acceleration of interest and predicting the maximum range and volume of snow experiencing that threshold for different charge heights.

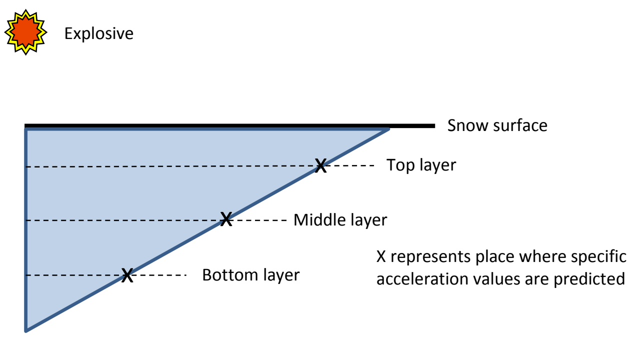

Figure 1. Schematic for influenced volume calculations. For a specific acceleration value, the range was predicted using the power law regression curves for each layer (X's on figure). Once the range in each layer was found, a linear curve was fit (through the X's) and extrapolated from the snow surface back to the blast axis through the snow depth (hypotenuse of the shaded triangle). By assuming axisymmetric conditions, the volume of affected snow was estimated by revolving the triangular area around the blast axis.

Using this technique, maximum ranges (at the surface) and snow volumes experiencing a specified value of acceleration (or greater) can be found. While the shape is approximate, it does give a reasonable estimate not only of the range of the explosive effect, but also the depth and volume. This is useful in evaluating different explosive placements while trying to maximize the probability of initiating an avalanche. Three different acceleration values (~ 1, 1.5 and 2 g's) were arbitrarily chosen to demonstrate the technique. While these acceleration values are arbitrary and not necessarily representative of actual values needed for artificial release, they are believed to be reasonable as they represent multiples of the gravitational load. They are also used to demonstrate the technique as other acceleration criteria could be implemented. Depth, range and volume results are shown in Table 2.

Table 2. Volume of hard pack snow influenced for specific values of acceleration and different detonation heights using a 0.9 kg charge.

Charge Height (m)	10 m/sec^2			15m/sec^2			20m/sec^2		
	Max Depth (m)	Range (m)	Volume (m^3)	Max Depth (m)	Range (m)	Volume (m^3)	Max Depth (m)	Range (m)	Volume (m^3)
0	1.1	11.9	158.7	1.1	8.6	87.9	1.1	6.8	58.2
0.5	1.2	11.5	168.8	1.2	9.1	104.6	1.2	7.8	74.6
1	1.2	11.7	165.4	1.2	9.4	108.1	1.2	8.1	80.1
1.5	1.1	14.5	244.4	1.2	11.1	150.8	1.2	9.1	107.7
2	1.1	16.2	292.4	1.1	12.3	169.9	1.1	10.2	116.3

In all cases, raising an explosive off the snow surface resulted in an increase in the maximum range and volume of snow within the acceleration criteria, but did little to increase the depth. Since the shockwave engagement geometry does not change significantly under the charge as it is raised, this is a reasonable result. While the maximum predicted range at the surface increased ~36-50% as the explosive was raised, the influenced volume increased ~80-100% (depending on acceleration criteria). As stated previously, this increased volume is the result of an average overpressure increase of only 25% from elevating the explosive. This is significant as not only the range increases (as is commonly believed in practice), but there is a substantial advantage in the volume of snow being impacted by the explosive. This increase is directly related to the probability of initiating an avalanche as weak layers or flaws within the snowpack are impacted. Increasing the snow volume directly increases the probability of finding an adequately sized flaw.

4. SUMMARY

This experimental program verified the well-known advantage to suspended explosives in avalanche control work, but provided additional insight and understanding on the effects explosives have in snowpacks. The overall snowpack dynamic response, as measured by the magnitude of resultant acceleration, increased up to 200+% for hard slabs. Vertical and radial attenuation curves were developed form the experimental data using TNT scaling law and power curve regression. Attenuation exponents were largely independent of charge height. Using the attenuation relationships, a method for predicting the maximum range and affected volume for a specified acceleration value was developed. For hard slab snow, raising the explosive resulted in a 36-50% increase in range and 80-100% increase in affected volume (depending upon acceleration criteria). The field data has been used to show the importance of explosive placement and how the affected volume, thereby probability of artificial avalanche release, can be greatly increased. The acceleration values used here were arbitrary, but future efforts could easily encompass realistic snowpack failure criterion. Additionally, additional instrumentation at multiple depths and ranges could be utilized to get more accurate acceleration regression data.

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