EXPLOSIVE SHOCK WAVE COMPRESSION IN SNOW: EFFECTS OF EXPLOSIVE ORIENTATION AND SNOWPACK COMPRESISON

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ABSTRACT: Explosives are crucial in the mitigation of avalanche hazards. A greater knowledge of the compressive effects of snow relative to explosive location and direction is needed for more effective placement based on snow pack configuration. Hand hardness tests and layer tracking were used to explore the compressive effects of explosives in snow. Four 2 lb charges were detonated at different locations and blasting cap orientations relative to determine the compressive effects of the shock wave. Results showed layer compression specific to the explosive location and blast orientation. It was confirmed that the air blast distributed the shock wave to the largest area most effectively; however, the surface shots produced the highest localized layer compression based on blasting cap orientation. Results showed that explosive location and orientation relative to the snow surface can be tailored for the best results based on the configuration of the snow pack. Further evaluation is recommended to produce more reliable results in a broader range of snowpack conditions.

KEYWORDS: explosives, layer compression, blasting cap directionality

1. INTRODUCTION

By observing weather and snowpack conditions, it can be determined when stresses within a snow pack are approaching the point of failure where avalanche could occur. Avalanche control technicians have used explosives to trigger small avalanches throughout the winter season in order to prevent formation of large, destructive avalanches. Moroz (1991) notes that explosive blasting increases the stress rapidly within the snow pack resulting in failure. Mechanical fracturing, explosive thrust, and/or shockwave pressure transmitted through the air, ground and/or snowpack can accomplish this. Moroz concludes that while use of explosives can be effective it is dependent on the method of delivery and placement.

Explosives are most commonly placed by hand in or just above the snowpack, moved into place using small tramways, or shot into place as projectiles. Determining whether the charge should be triggered within or above the snowpack can be a crucial and difficult decision. Lyakhov et al (1989) have determined that explosive waves in snow smear upon propagation. The wave velocity decreases quickly and significantly compared to the same wave traveling through air. The snowpack shows properties similar to a nonlinear viscoelastic material or acts like a giant sponge, Wilbour (2002). In addition, snowpack composition and temperature factor into shockwave propagation. Shockwave dissipation increases with temperature and hardness though exact relationships have not yet been determined. It must also be noted that shockwaves do not propagate uniformly from charges. The greatest velocity waves emanate from the end where the blasting cap is placed. Little published research exists relating blasting cap orientation to effectiveness of a charge.

2. MATERIALS AND METHODS

The experiment was conducted at Alta, Utah in the spring of 2006. A flat study plot (0˚ slope, no aspect) in Albion Basin approximately 25m x 25m was marked off one month prior to the test date to minimize skier impact. The experiment was conducted at 2600m above sea level between 7:30 AM and 1:30 PM with clear skies, no wind and no precipitation. The surface conditions changed from a 5 cm thick, knife hard, melt freeze crust at 7:30 AM to a fist/4-finger hard layer at 1:30PM. A 150 cm deep control pit inside the study plot was profiled recording grain type, size and density for each layer.

Four 2 lb DYNO C90 cast booster charges were used. Explosives were detonated on the melt freeze crust surface between 7:30 and 8:30AM in the following orientations: 1 meter above the snow surface blasting cap down, on the surface blasting cap up, on the surface blasting cap down, and 0.5 meter below the surface blasting cap up (Shots 1, 2, 3, 4, respectively). Shot 1 was measured at 1 meter above the surface using bamboo and Shot 4 was buried using a posthole digger and back filled. Charge placements were photographed and detonations were video recorded.

C90 DYNO Cast Booster

Weight	0.9 kg (2 lb)
Density	1.66 g/cc
Detonation Velocity	7,270 m/s (23,850 ft/s)
Detonation Pressure	220 Kbars
Energy	1,880 cal/g

After detonation, crater dimensions were recorded and craters photographed. Craters were profiled from their vertical centerline directly outward to a distance of at least 1m [*Fig. 1*]. A standard, 240cm avalanche probe was used to mark the center of each crater prior to pit construction. Snow pits were cut facing N/NW to shade the sample walls. A reference layer (showing alteration from the explosive) 75-80 cm deep was selected to standardize layer location for comparison between craters. Hardness, wetness, and grain form were recorded for each identifiable layer at five different distances from crater centerline. Residual black powder/snowmelt in the crater center, combined with the probe hole provided a "highlighting effect" of the stratigraphy. Profiled craters and sample walls were photographed for further comparison.

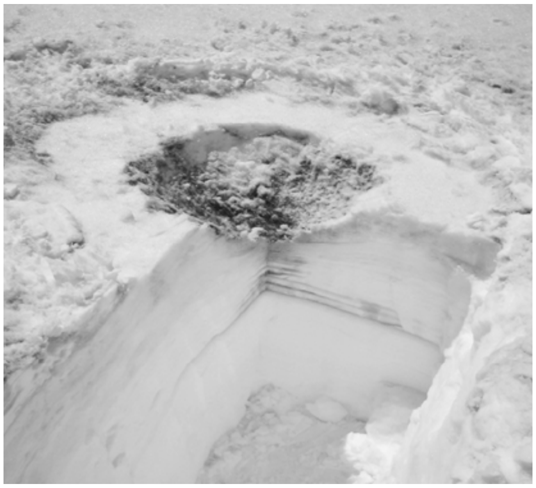

Figure 1. Photograph of crater profile technique, illustrating sample wall intersection with crater centerline and highlighting effect.

3. CALCULATIONS

Percent compression per layer was calculated for the comparison between blasting cap orientations. The thickness of each layer was assumed to be constant at a distance of 100 cm from the crater centerline, as stratigraphy beyond this distance was unaltered in each of the four pits. A layer thickness model was then created to illustrate the compression of each layer over distance *x* from the crater centerline by [*Eq.* 1]:

$$\left(\frac{t_{x=100cm}-t_x}{t_{x=100cm}}\right)*100=\%\ \text{Compression}$$

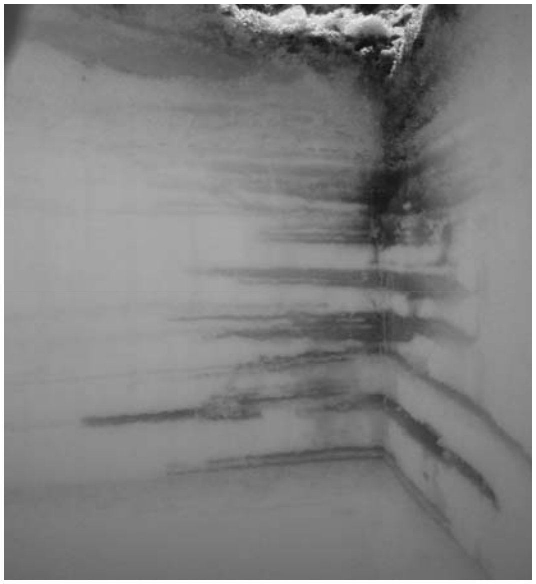

Figure 2. Photograph illustrating highlighting effect in Shot 2 blasting cap up sample wall.

Figure 3. Photograph illustrating highlighting effect in Shot 3 blasting cap down snow profile.

4. EFFECTS OF BLASTING CAP DIRECTIONALITY

4.1 Results

Only the first 3 shots were successfully profiled due to the large temperature change on the day of the experiment. Profile results from Shot 1 were deemed inconclusive because pit was not profiled out to a stead layer thickness. Furthermore, a greater variation in layer hardness was expected than observed, thus hardness measurements were difficult to quantify and appeared constant from x=0 cm out to x=100cm.

One comparison was made for the effects of directionality between surface Shot 2 blasting cap up and surface Shot 3, blasting cap down. *Fig. 1/2/3* illustrate the highlighting effect that occurred during testing, which aids in the visualization of layer compression. Highlighting occurred as carbon particles trapped in the water percolated down through the layers. Black layers were identified as wet layers with decomposing polygrain forms.

The resulting snow profiles were compiled to illustrate layer locations for each individual crater over a distance of 100 cm from the crater centerline, x=0 cm. See *Fig. 4/5* for layer location graphs of Shots 2 and 3 respectively. Layers are labeled alphabetically starting at the reference layer, followed by the number 2 or 3, which identifies the shot.

The blasting cap up results show layer location changes as deep as layer E2 located at 17 cm; however, layers D2 (15 cm) and below remain at a constant locations out to x=100 cm. Other layers such as J2 appear at the edges of the crater around x=14 cm showing the layer removal that occurred in upper layers due to the blast.

The blasting cap down results [*Fig. 5*] show layer location changes as deep as layer B3 located at 6 cm from the reference layer. Layers up to F3 translate down towards the reference layer. New layers G3 and H3 appear at the edges of the crater again showing the layer removal that occurs in upper layers closest to the blast. Layers and letters only match for layers A through D.

The percent layer compression graphs for Shots 2 and 3 [*Fig. 6/7*] show a larger percent compression with the blasting cap down. Compression graphs also show that layers B2, C2 and C3 exhibit zero percent compression. Layers A2 and A3 were omitted to clarify the graph.

4.2 Discussion

Blasting cap orientation directly effects layer compression. By comparing *Fig. 6* and *7*, the overall percent layer compression seen in the blasting cap down profile is much larger than with the blasting cap up. Top layers H2 and F3 appear to compress significantly, but some of the change in layer thickness can be attributed to layer removal. Layer F2 compressed 21% at x=0 cm where as the same layer E3, identified by the same grain type, compressed 31% at x=0 cm. Furthermore, the layer compression seen with the blasting cap down is evident deeper in the snow pack and further from the centerline of blast. For example, the percent compression in layer B3 at 8 cm from the reference is approximately 60% at x=0 cm, 40% at x=14 cm and 20% at x=28 cm. The compression with the blasting cap up only visibly effected layers as deep as E2 at 20 cm; furthermore, the compression experienced was only 15% at x=0 cm and no compression at x=14 cm. Therefore, blasting cap down orientations produce larger compression effects deeper into the snow pack and further from the vertical blast axis. The direction and correlation to layer compression is a result of blast stress wave attenuation.

Some layers seem to resisted compression. Layer D3 of *Fig. 5*, blasting cap down, did not compress though the layer translated deeper into the snow pack. Layers C3 and B3 just below D3 compressed 50% and 60% translating D3 down 5 cm while remaining 2 cm thick. Layer D3 was identified as a polygrains/melt freeze grains, which are characterized as high strength grain clusters. The same layer was identified in Figure 8 as layer D2; however, the compression effects were not seen at that depth. In addition to grain

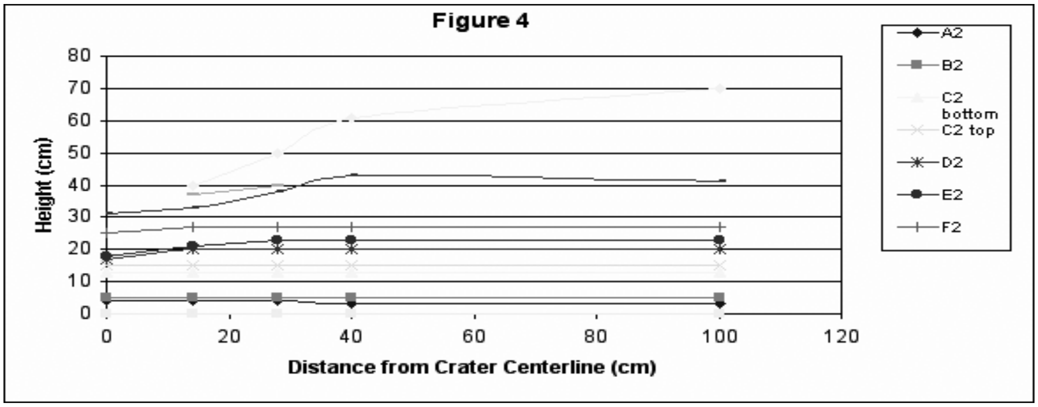

Figure 4

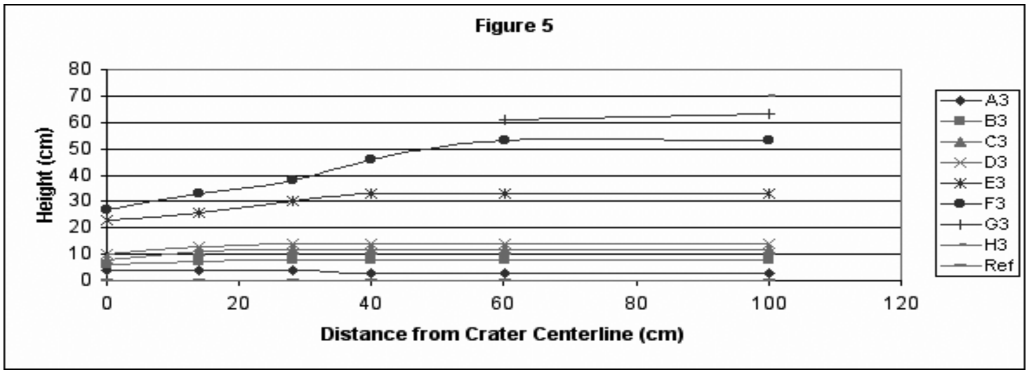

Figure 5

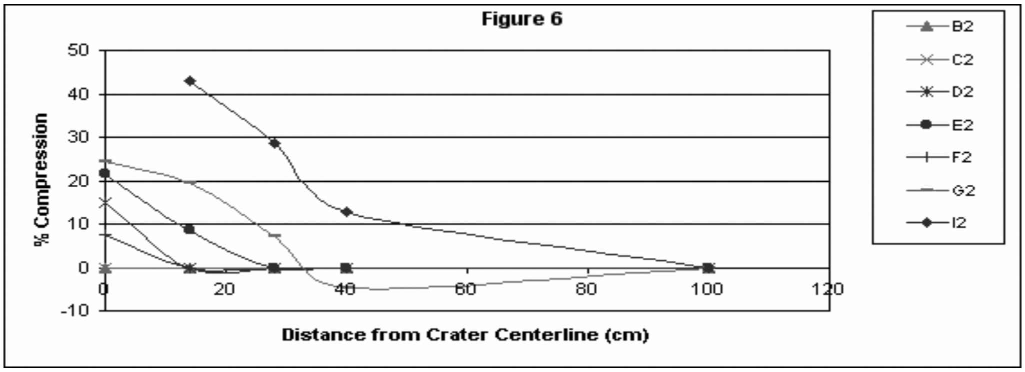

Figure 6

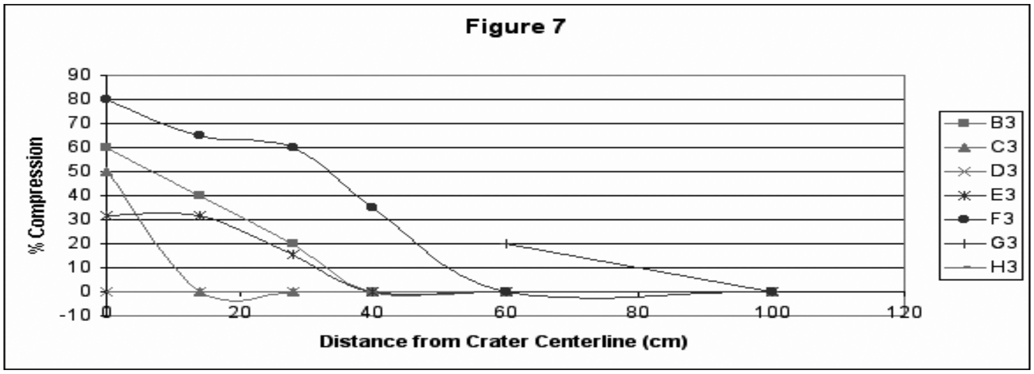

Figure 7

similarities, both layers resisted highlighting seen in *Fig. 2* and *3*.

Highlighting was not an anticipated effect. It is assumed that because of the clear and sunny conditions the black carbon particles peppering the snow caused the snow to melt as a result of radiant heating. Water then saturated the bottom of the crater and percolated down through the various layers saturating funicular grain clusters highlighting or turning them black and passing pendular grain clusters which remained white.

5. EFFECTS ON CRATER DIMENSIONS

5.1 Results

Resulting craters were photographed for comparison within 60 seconds of detonation [*Fig. 8-11*]. Crater size and dimension varies with location and direction of the charge. The dimensions for the four craters were also recorded and are presented in *Table 1*.

Table 1: Crater dimensions

Charge Location, Cap Orientation	Shot 1 1 m, down	Shot 2 surface, up	Shot 3 surface down	Shot 4 -0.5 m, up
Crater depth (cm)	11	31	35	80
Crater diameter (cm)	119	83	90	240
Inside diameter of surface debris ring (cm)	200	180	155	NA

Figure 8. Debris and resulting crater from Shot 1 at 1m, blasting cap down.

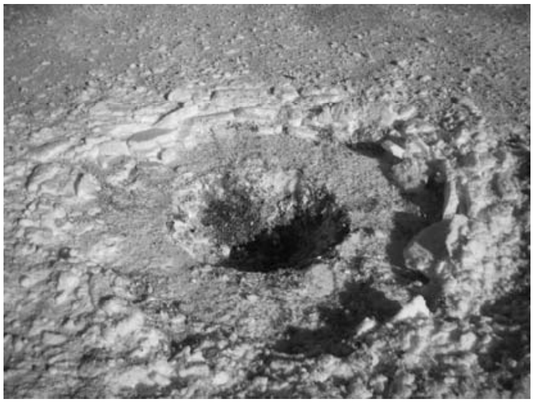

Figure 9. Resulting crater from Shot 2, surface, blasting cap up.

Figure 10. Resulting crater of Shot 3, surface, blasting cap down.

Figure 11. Resulting crater of Shot 4 blasting cap up buried at 0.5 meter below surface.

5.2 *Discussion*

The depth and diameter of each crater correlates directly with the location of the charge. At 1 meter, Shot 1 only penetrates the snow pack 11 cm; however, the crater diameter is 119 cm. The two surface shots have similar visual results leaving 31 cm and 35 cm craters and successfully penetrating deeper into the snow pack than the 1-meter shot. In contrast the surface shots left smaller diameter craters than the 1-meter shot. The 1-meter shot, blasting cap down, affected a larger surface area due to the greater distance from the surface at detonation. Furthermore, a less concentrated force acted upon the surface than the surface shot resulting in a wide shallow crater.

The effects of directionality on the surface shots are visible in the crater dimensions. With the blasting cap down the crater was approximately 11% deeper and 7% larger in diameter. However, the debris ring was 16% smaller with the blasting cap down confirming that most of the force was directed into the snow pack and lifting less snow.

Comparing the depth of observed compression for the two shots blasting cap up it is apparent that they both penetrate snow pack similarly. The depth of crater four is 80 cm and the explosive was buried 50 cm below the snow pack surface, so the depth into the snow pack the charge displaced was 30 cm. The resulting crater depth of the surface shot was 31 cm which is very similar to the buried shot, illustrating similar blast stress wave attenuation properties. The buried shot did not visually disrupt the 5 cm melt freeze surface crust outside of the crater, where as the previous three shots left a rippling effect at the surface.

6. SUMMARY AND CONCLUSIONS

Results indicated that explosive location and orientation relative to the snow surface can be tailored for the best results based on the configuration of the snow pack. Placing the blasting cap oriented down produces larger compression effects deeper into the snow pack and in a larger radius from the vertical blast axis. The direction and correlation to layer compression is a result of blast stress wave attenuation.

Future testing is recommended to better characterize layer compression in varying snow pack conditions under varying snow conditions. Additional research to explore specific crystal structure change of compressed layers and achieve a better understanding of compressive behaviors of different grain types is also recommended.

7. ACKNOWLEDGEMENTS

We would like to thank the snow safety program at Alta Ski Resort and Dan Howlett (Howie) for making this project possible; as well as Ralph Patterson, Newel Jensen, and the University of Utah for offering Geography 5260 – Snow Dynamics & Avalanche Studies.

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