INFLUENCES OF OVERLYING SLAB THICKNESS ON THE SNOW MECHANICS OF BRIDGING PROPENSITY
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ABSTRACT: Almost all snow avalanche fatalities are human induced. Regardless of the mode of travel, moving over snow cover results in a localized dynamic load (LDL) to the snowpack. Localized loading can cause failure initiation and fracture propagation in weak layers, and possibly trigger avalanches. Prior to this study, research regarding the influence of overlying slab thickness in relation to snow cover bridging propensity and snow mechanics had not been investigated in the field. Finite element modeling and various field studies confirm that snowpack bridging causes the transmission of an LDL to be dispersed across a stiffer overlying slab, decreasing penetration, and with it, the likelihood of avalanche initiation. This study explores the relationship between varying overlying slab thickness and snowpack bridging propensity. By using force resistors and particle tracking velocimetry techniques, we were able to collect stress attenuation and snowpack displacement data while manipulating overlying snow slab thickness under a fixed skier band load. Stress and strain data collected during field experimentation in the winters of 2019 and 2020 in the San Juan Mountains of Colorado suggest that measured stress and strain increase with decreasing overlying slab thickness. Additionally, PTV techniques provide insight into the complicated relationship between changing slab thickness and snowpack deformation rheology, suggesting that the strain response to changing thickness is complex and dynamic. Our results suggest that under a given LDL, decreasing slab thickness is directly correlated with increased stress at a given depth, as well as augmented deformation and strain to the snow cover.

KEYWORDS: snow mechanics, bridging propensity, particle tracking velocimetry, fracture initiation.

1. INTRODUCTION

Roughly 93% of snow avalanche fatalities are human induced (Tremper, 2008). Whether it be backcountry skiing, snowboarding, snowshoeing, or snowmobiling, traveling over snow cover results in a localized dynamic load (LDL) to the snowpack. Localized loading can cause failure initiation and fracture propagation in weak layers, and possibly trigger avalanches. The stress pulse induced by loading is primarily dependent upon (1) the type of trigger loading the snow, and (2) the medium that the load attenuates through. Bridging causes the transmission of the band load delivered by a backcountry traveler to be dispersed and spread out over a stiffer slab, decreasing penetration, and with it, the likelihood of an avalanche. By quantifying the stress and strain within a snowpack induced by an LDL to a mountain snow cover, the experimentation conducted during this study explores how overlying slab thickness affects load attenuation and the snow mechanics of the bridging phenomenon.

The concept of snowpack bridging was first brought to the surface by (Schweizer, 1993), using finite element modeling to show how stiffer layers concentrate stress from localized loading and also form a “bridge” which reduces the depth at which a load would penetrate the snowcover. This concept was later confirmed by Camponovo and Schweizer (1997), and Schweizer et al. (1995a) Schweizer et al. (1995b), who inserted load cells in the snow cover in an effort to more accurately quantify stress under a LDL. Results confirmed the effects of bridging, that stress attenuation decreases with depth, and that dynamic loading stresses the snow cover more so than that of a static nature. Later Schweizer and Camponovo (2001) used the same load cells to measure and define the “skier's zone of influence”; the area where a skier is capable of initiating fractures in weak layers. Their research showed the zone is relatively small on average, approximately 0.3m^2–0.5m^2, but did not address the effects of bridging propensity on the skier stress bulb.

Prior to this study, research regarding the influence of overlying slab thickness in relation to snow cover bridging propensity and snow mechanics had not been investigated in the field. This study aims to use further examine these relationships by gathering stress attenuation and

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snowpack displacement data under a fixed skier band load while manipulating overlying slab thickness. Using force resistors inserted in the snowpack and a camera pointed at the snowpit wall, we were able to gather stress and strain data while manipulating overlying slab thickness. Schweizer (1995) also employed the use of early strain field mapping via video particle tracking. Much more recently, Birkeland et. al. (2019) used particle tracking techniques to inquire about temporal changes of snow mechanics after differential loading. They used particle tracking to follow changes in snow mechanics with increased load. This study uses particle tracking techniques to investigate snowpack deformation from a fixed load and how variation in overlying slab thickness relates to snowpack bridging.

2. FIELD AREA AND METHODS

2.1 Field area

Field experimentation was conducted during the winter of 2019 and 2020 in the San Juan Mountains of Colorado, at the mouth of La Plata Canyon about twenty miles Northwest of the town of Durango. Data collection occurred below treeline in a flat open meadow at 8,900ft, where effects of wind redistribution of snow were negligible. Data was collected in open clearings, as well as below tree canopy.

2.2 Stress and strain instrumentation and measurement

To measure LDL stress data, we used two single point force resisting load cells attached at the end of 2ft aluminum stakes (Figure 1) which were then inserted into the snowpack perpendicular to the pit wall (Figure 2). Stress data was collected and logged to a portable field computer.

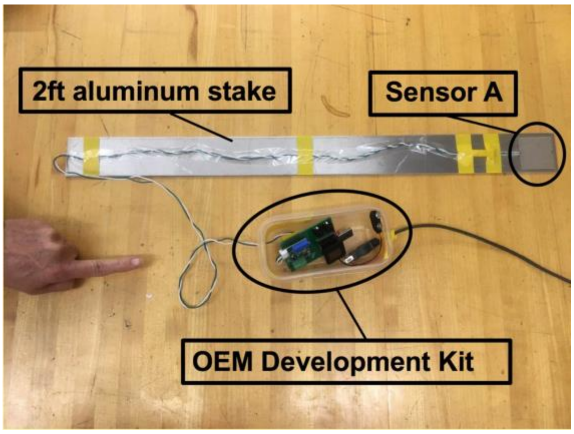

Figure 1. *Stress Instrumentation*. Stress measurement instrumentation including load cell A (.02kg-5kg, 39.70mm^2) mounted to the end of a 2ft aluminum stake, and the OEM development kit used to log stress data.

Snowpack displacement from the skier band load was collected using particle velocimetry techniques, where an array of high contrast square particles were inserted into the pit wall to provide fixed points to track during displacement. High resolution 30fps video recordings were captured during the loading process, and a PTV algorithm developed by Dr. Ron Simenhois was later used for data analysis to track particle displacement, a proxy for measuring strain and potential snowpack deformation character.

Figure 2. *PTV software particle prioritization and tracking procedure*. A screen capture from the live particle tracking process to illustrate particle corner prioritization and associated number scheme.

2.3 Artificial slab formation

Due to the specificity of the snow pack regime required to conduct stress and strain experimentation, and the logistical difficulties of loading and removing portions of the overlying slab, artificial hard slabs were manufactured prior to data collection field days. Schweizer and Componovo (2001) found the average skier stress bulb to be 0.3m-0.5m deep. Subsequently, artificial slabs were piled and compacted to at least 50cm to ensure the upper range of skier load attenuation was met and/ or exceeded. The slabs were left to sinter and harden for varying time spans ranging from three days to two weeks before returning to conduct stress and strain experimentation.

2.4 Experimentation procedure

The experimental procedure involved digging into the snow cover and performing a full scientific snow profile including density measurements every 10cm. The density of the 4 artificial slabs averaged 365 kg/m^3 . Slabs were formed over multiple kinds of weak layers and snowpack configurations, but were primarily composed of near surface facets and mixed forms. After placing tracking particles in a grid array across the pit wall, load cells were placed into the front pit wall 5cm above the artificial slab and weak layer interface. The author, weighing 72kg, applied the LDL by stepping onto a single ski directly over the load cell, waiting three-five seconds, then stepping off. The ski was located perpendicular to the front wall of the snow pit (Figure 3).

After the initial loading event, 10cm of the overlying slab was removed using a snow saw to lessen the bridging effect (Figure 4). The slab was then loaded again. This process (of loading and shaving off 10cm) was repeated for 40cm, 30cm, 20cm, and 10cm slabs.

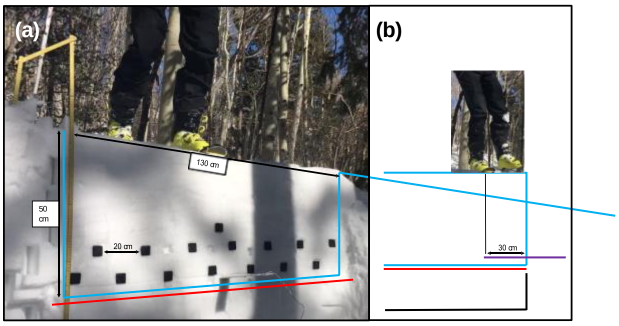

Figure 3. *Snow pit setup and layout for experimentation.* (a) The senor was placed in the center of the front pit wall, ~5cm above the artificial slab/ weak layer (red dashed line) interface. PTV particles were placed 20cm apart. Sometimes rows were staggered or placed directly on top of one another. (b) The sensor was pushed 30cm into the snowpack, where the load (not to scale) was applied by stepping onto a ski directly above the sensor.

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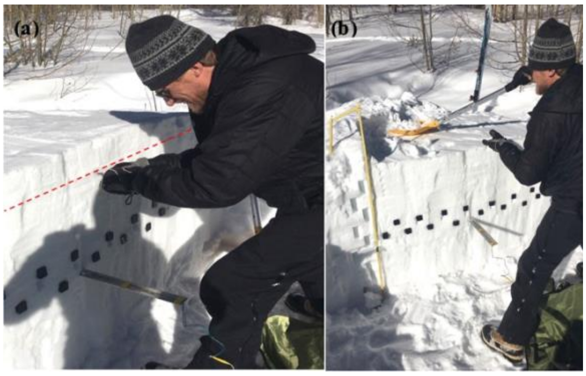


Figure 4. *Slab removal process.* (a) Cutting 10cm down from the slab surface with a snow saw (red line). (b) Removing 10cm from slab surface with a shovel.

2.5 PTV data manipulation and analysis

Further manipulation of the particle (x,y) position data using Microsoft Excel allowed for the derivation of vector and strain information regarding the snow deformation process during the initial loading period, when the most deformation is likely to occur. By analyzing deformation during the initial loading period for different slab thicknesses, larger patterns and trends regarding the influence of slab thickness on snowpack bridging and snow mechanics as a whole became more readily apparent.

3. RESULTS & DISCUSSION

3.1 Stress data

Due to limitations with the stress sensing equipment, the conclusions drawn from the stress data are also limited, and preliminary at best. However, the average stress measurements of variable slab thicknesses do support previous research that stress attenuation is a function of slab thickness, where load cells began to register a response as overlying slab thickness decreased. Preliminary data here show a stress attenuation threshold for artificial slabs between 20cm-50cm. This is consistent with Schweizer and Jameison, (2003), who found the average skier stress bulb to be 0.3m- 0.5m. (FIGURE 5). This information suggests the bridging effect decreases stress attenuation, which is also congruent with previous research.

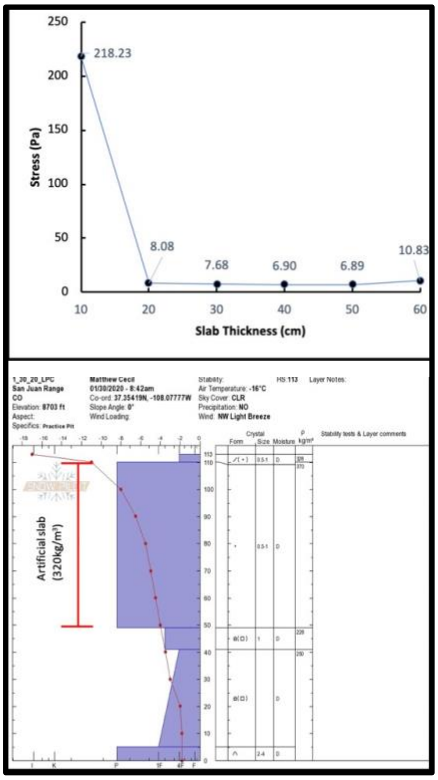
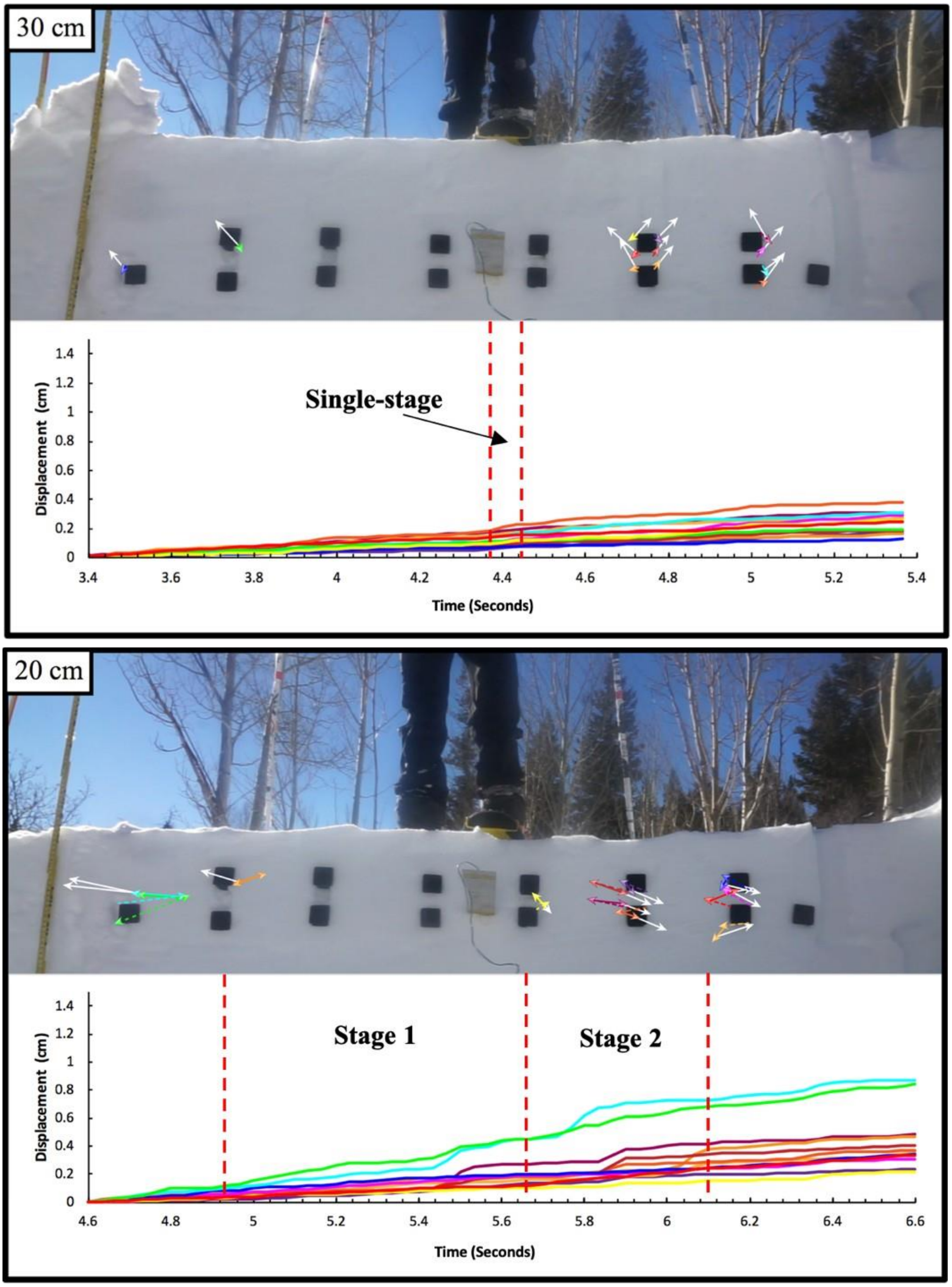


Figure 5. ***Stress plot and associated snow profile.*** Average maximum stress with slab thicknesses 10cm-60cm for a field day on January 30th, 2020, as well as associated snow profile information. This plot shows stress attenuating before reaching the sensor for slabs as thin as 20cm, where the sensor surpassed its load capacity for slabs thinner than 20cm. This artificial slab had an average density of 320kg/m^3.

3.2 PTV strain data



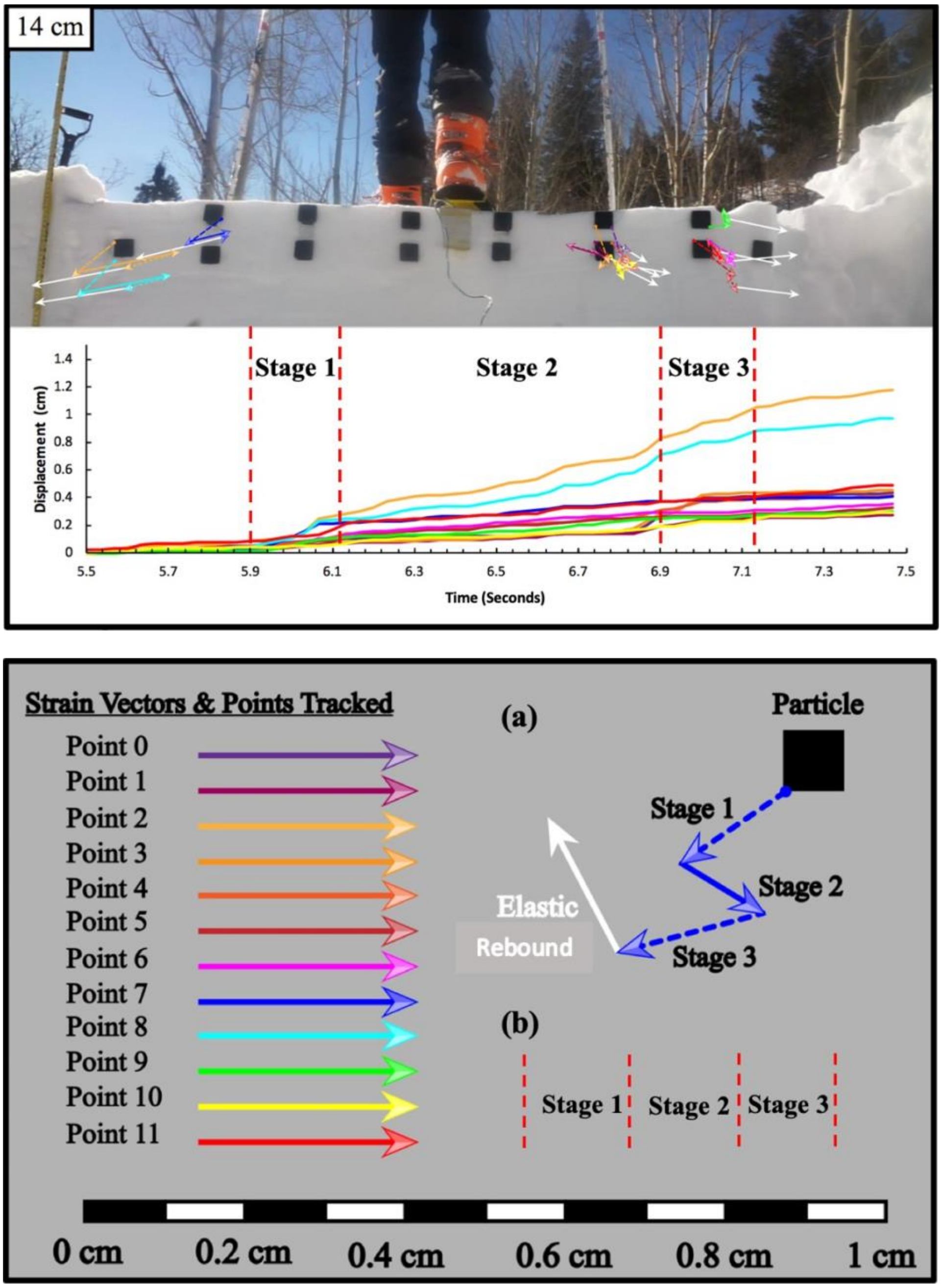


Figure 6. ***Vector fields and hysteresis plots for total displacement.*** Above are displacement vector fields (upper half of each figure) and displacement hysteresis plots (lower half of each figure) for loading events for 30cm, 20cm, 14cm slabs. Measured in cm in a 2D (x,y) plane, the displacement vector fields show the movement of each particle when significant displacement took place during the "initial loading period". (b) The red dashed lines in the lower half of each figure denote when significant displacement occurred during the initial loading period. Significant displacement lasted 0.12 seconds for 30cm, 1.05 seconds for 20cm, and 1.1 seconds for the 14cm slab iteration. The hysteresis plots show displacement over time for each particle during the same period, where displacement for each particle is color coordinated between vector field and hysteresis plot. The vector fields show the character of deformation during the periods of significant displacement, displaying both single stage and multiple stage particle displacement. Thicker slabs show more uniform deformation in shorter 0.1-0.2 second periods (single stage), while thinner slabs display strain in multiple directions that is more fragmented and step like (multiple stages), occurring over longer periods of time (~ 1 second). (a) If deformation occurred in multiple stages, each stage is symbolized by alternating dashed and solid lines, where the first and third stage are dashed and the second is solid. Finally, the white vectors show the strain response of each particle upon the initiation of load removal (not shown in hysteresis plot).

3.2.1 Deformation character and rheologic observations

Variations in overlying slab thickness not only seems to affect bridging propensity, but also appears to influence the character of deformation and rheologic response of the snow to a dynamic load. Deformation of the 50cm, 40cm, and 30cm slabs under an LDL show a very different response compared to the 20cm and 14cm slabs. For load iterations on thicker 50cm-30cm slabs, the subsequent strain happened in a shorter amount of time (0.12-0.24 seconds), and particles showed deformation in single stages of displacement in a synchronous and uniform manner (Figure 6). The deformation for 20cm and 14cm slabs happened over a longer period time (1.05-1.10 seconds), where displacement appeared to be less synchronous between particles, deforming in a more step like and discontinuous manner. Figure 6 illustrates particle strain for 20cm and 14cm slabs showing two and three stages of deformation where each particle moves in multiple directions during a single loading event in the vector fields, as opposed to a single stage of uniform direction for thicker slabs. This suggests that thicker (greater than 30cm in this case) hard slabs behave and deform with a viscoelastic rheology up until a point. At some thickness (between 30cm-20cm slab thickness for this slab) the rheologic response changes and exhibits plastic deformation where failure initiates after surpassing a yield threshold. This "step like" deformation character found in thinner (less than 30cm thick) slabs is consistent slabs is consistent with Yosida et al., (1958). The rheology of this artificial slab can be thought of as stepping onto wooden boards of various thicknesses. The thicker boards bend slightly, then quickly rebound to their original shape after load removal. The thinner boards tend to bend and then crack in multiple stages, breaking to a point where rebound becomes less possible (plastic behavior).

3.2.2 Viscoelastic deformation

For each load iteration for 50cm-14cm slabs, the PTV results show a strain response while removing the LDL from the slab. This elastic response to stepping off of the slab is congruent with the viscoelastic nature of snow. However, the elastic response appears to change with slab thickness as well. For slabs 50cm-30cm thick, the vector fields show the slab rebounding back upward towards the default state (Figure 6). However, in the 30cm-20cm slab transition, the character of the elastic response changes along with the viscoelastic- plastic rheologic transition mentioned previously. During the 20cm slab loading event, the displacement vector field shows the particles moving downward, as opposed to upward in response to load removal (Figure 6). The same trend is apparent for the 14cm slab response. This downward displacement in response to load removal is consistent with the plastic rheology of the thinner slabs. The strain response is likely in the downward direction because complex slab failure (likely a combination of brittle and ductile viscoelastic failure) has prohibited an elastic rebound response from taking place.

3.2.3 PTV limitations and error

The raw data output from the particular PTV tracking software utilized in this study is rather rudimentary, requiring extensive manipulation and analysis to find patterns and trends in the displacement data. Because of this, the vector data in this study is subject to significant human interpretation, providing room for human error. The PTV software used offered limited control over particle corner prioritization, which often resulted in an incomplete array of particles being tracked (Figure 2 & Figure 6). This limits the full picture of what is happening during the deformation process, and leaves room for error when making interpretations.

4. SUMMARY

This is a proof of concept study combining the measurement of stress attenuation from a dynamic band load with the resultant displacement and deformation in the snowpack to observe complex relationships in snow mechanics related to bridging. These measures were used to assess the effects of changing overlying slab thickness on slab bridging propensity in the field. This study confirmed much of what others have already done, verifying that stress attenuation decreases with slab thickness, and strain and displacement generally decrease with increasing slab thickness as well. PTV particle tracking techniques helped provide insight into the effects of variable slab thickness on snow cover deformation character and rheology. The study found that in a snowpack structure with a thick hard-slab comprising the top 50cm of the snow cover, strain accumulation causes snowpack deformation to decrease up until a point. After this point, total strain during the initial loading period increases again resulting in larger amounts of displacement. This change in displacement with lessening slab thickness is likely an artifact of a change in rheology, where there appears to be a yield threshold separating viscoelastic deformation and plastic deformation. At this yield threshold, deformation deviates from a quicker more uniform strain response in the snowpack to a slower and less synchronous, more sporadic and "step like" response. This variance in rheology with slab thickness is also apparent in the elastic strain response, where instead of producing elastic rebound like in a thicker slab during load removal (viscoelastic behavior), the response is primarily continued downward movement, a likely result of plastic failure.

4.1 *Implications of this study*

This study reinforces previous assumptions that In regard to bridging propensity, thicker overlying slabs can withstand greater dynamic loads before reaching plastic failure. In regards to travel in avalanche terrain, avalanches are less likely to be initiated when traveling over thicker portions of a slab where the “bridge” is strongest, and the attenuation of a stress bulb is less for a given band load. However, it is important to note that these concepts should be applied with caution due to the inherent spatial variability of snow cover in and around avalanche terrain, where thinner slab margins with less bridging propensity can be difficult to predict.

4.2 *Further research*

Using more accurate and precise instrumentation to measure the stress and strain on a snowpack, as well as more streamlined analysis techniques would help to better investigate these complicated snow mechanics relationships. A more advanced PTV as well as particle image velocimetry (PIV) techniques would also help better dissect these relationships. Furthermore, stress and strain experimentation with natural slabs instead of artificial ones would provide a more representative interpretation on the real world applications of this study.

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