PARTICLE IMAGE VELOCIMETRY; A NEW TECHNIQUE TO MEASURE STRAIN IN LOADED SNOW

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ABSTRACT: A new technique has been developed to accurately measure strain in snow subjected to a band load. While stress beneath loaded snow has been measured, accurate measurements of strain have only been evaluated posthumous to the application of the load. A 0.156 m^3 sample of snow was placed into an aluminum cube with a clear lexan side and loaded from above with a 0.025 m^2 band load. The displacement caused by the loading was calculated using particle image velocimetry (PIV) in which particle paths are traced with a rapid sequence of digital photographs. This technique utilizes a method of non-intrusive velocity measurements designed for the measurement of flow velocities in fluids. The medium must be seeded with tracer particles in order for the software to follow the reflected light of each tracer particle as it moves under a band load. A digital camera is used to capture one plane of displacement transverse to the band load through the clear lexan wall. A sequence of digital images is collected while the snow is loaded from above. The PIV post-processing software is able to follow individual tracer particles both spatially and temporally. The output from the PIV software generates a vector field that allows conversion of displacement to a strain field. Various experiments were conducted with layers of different density, crystal type and resistance (hardness) of snow. The strain fields show a distribution of the band load that varies with snow surface layer density and resistance. Strain is shown to concentrate at snow layer boundaries.

Keywords: snow strain, particle image velocimetry, snow load

INTRODUCTION

The rheological properties of snow are not well understood and constitutive relationships are not developed enough to explain the mechanical behavior of snow under varying loading conditions. Better understanding of snow mechanics is useful for various fields including vehicular movement over snow, calculating snow loads on structures, avalanche studies and military applications (Shapiro, et. al. 1997). There is a phenomenon in the avalanche field that most people call “Bridging”. This is a situation where a hard, dense layer, or slab of snow, overlies a less dense, weaker layer, but the hard slab is thick enough or rigid enough to support the weight of a person or vehicle. This hard slab layer forms a sort of bridge that distributes the load on the surface and prevents it from affecting the lower layers of the snowpack. A “bridge” in effect, prevents the weight of a person from initiating an avalanche even though there is a weak layer somewhere in the lower part of the snowpack. While “bridging” is a phenomenon that has been frequently observed by avalanche specialists, it is not well understood. There has been little formal research directed at determining just how thick and rigid a hard slab must be to attenuate or distribute a load on the snow surface.

Various workers have studied the response of snow to vertical loading. Yosida (1956) investigated the mechanical properties of snow using a piston to penetrate snow in order to define the limits of the pressure bulb in which the snow was disturbed. Brown (1979) used a volumetric constitutive law for snow to demonstrate the specific power needed for vehicle mobility in snow where the pressure bulb is assumed to reach the ground surface. Fohn (1987) developed an equation to calculate shear stress beneath a skier and showed a modeled stress bulb through a snowpack beneath a load. Schweizer (1993) calculated skier induced stress distribution using finite element modeling. More recently Schweizer and Camponovo (2001) put load cells in a

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snowpack beneath a skier to measure stress distribution below a skier. While there has been success in measuring stress beneath loaded snow, empirical measurements of strain beneath loaded snow have only been performed posthumous to the loading. Previously, researchers have not been able to accurately measure strain within the stratigraphy of the snowpack.

METHODS

A new technique to measure displacement of snow under a band load has been developed using particle image velocimetry. Particle image velocimetry (PIV) is a technique which utilizes a method of non-intrusive velocity measurements designed for the measurement of flow velocities in fluids. A fluid is seeded with tracer particles such as oil or small solid particles. These tracers are illuminated by a plane of laser light in a moving fluid. A series of sequential digital images are taken at rates of up to 15 times per second. Image processing algorithms follow the tracer particle's displacement between images. Post processing software computes displacement vectors between 2 sequences of images to produce a field of displacement vectors. The displacement field is measured locally across the field of view of the images, scaled by the image magnification and then divided by the known pulse between images to calculate flow velocity at each point (Keane and Adrian, 1992). The PIV software automatically calibrates the interrogation window that is used to follow the particle image through space.

Because PIV must utilize images of a plane to calculate flow, I realized that PIV could be used to measure displacement on a plane of snow under a load. To accomplish this, I constructed a 0.156 m^3 aluminum box with a clear lexan side that allows snow to be loaded from above and displacement observed in the layers below (Figure 1). Snow is loaded with a 0.025 m^2 aluminum plate (0.08 m by 0.25 m) attached to a piston that exerts a vertical force downward into the box of snow.

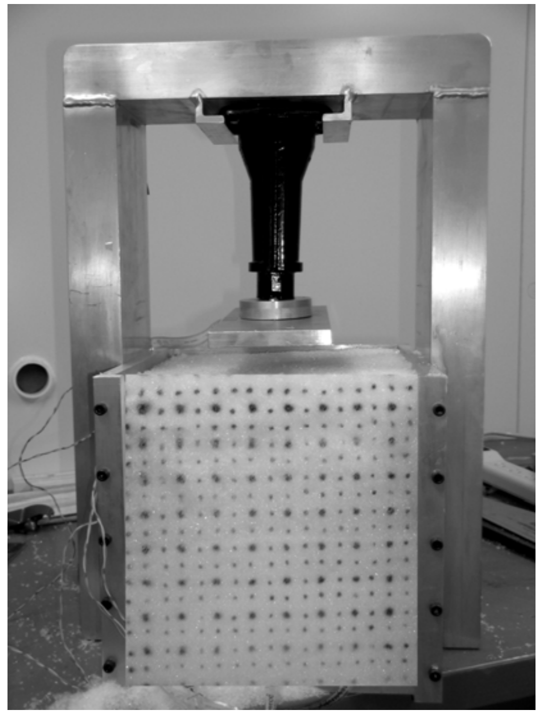

Figure 1. Snow loading apparatus with seeded snow visible through lexan. Piston pushes downward into snow. Height and width of snow is 0.25 m.

Snow grains by themselves did not have enough contrast for the PIV camera to accurately measure displacement. Snow was seeded using a 0.01 m grid of painted dots. A digital camera, hooked up to a dedicated computer, took a rapid sequence of photos of the snow through the clear lexan wall as the snow was loaded from above. The PIV software generates a field of vectors that shows the actual displacement of the snow through time (Figure 2). The displacement can easily be converted to strain to create a picture that shows how the load affects the snow (Figure 3). With this technique, I can measure exactly how a load on the surface affects a layered snowpack.

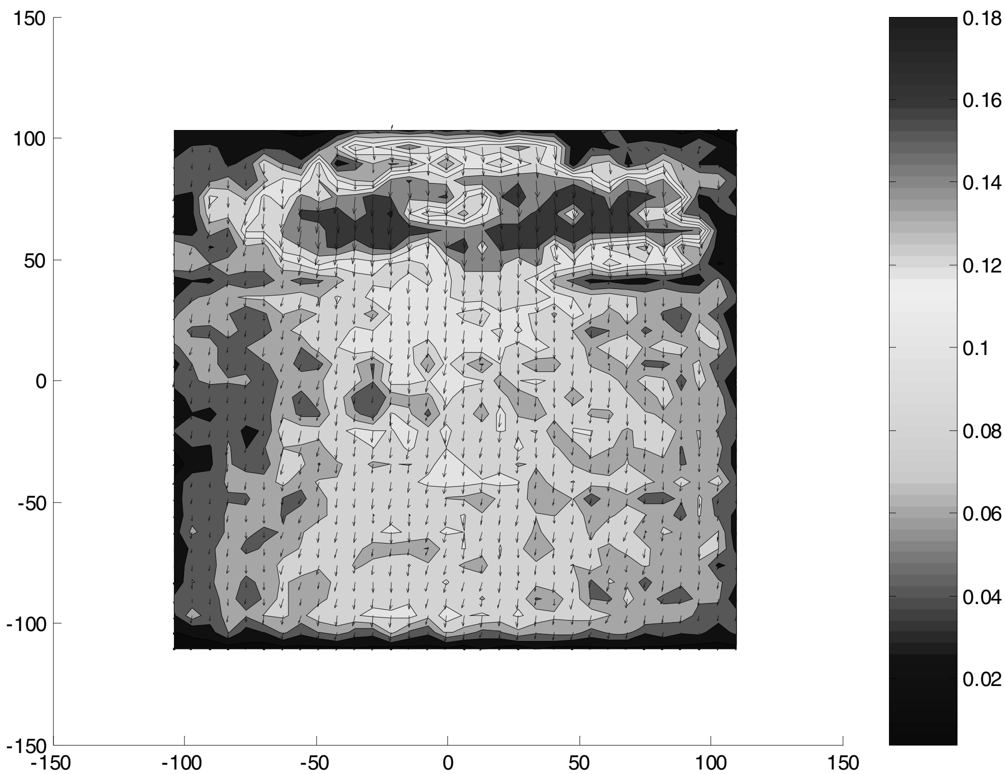

Figure 2. Displacement in a layered snowpack from vertical loading. (Scale is in mm).

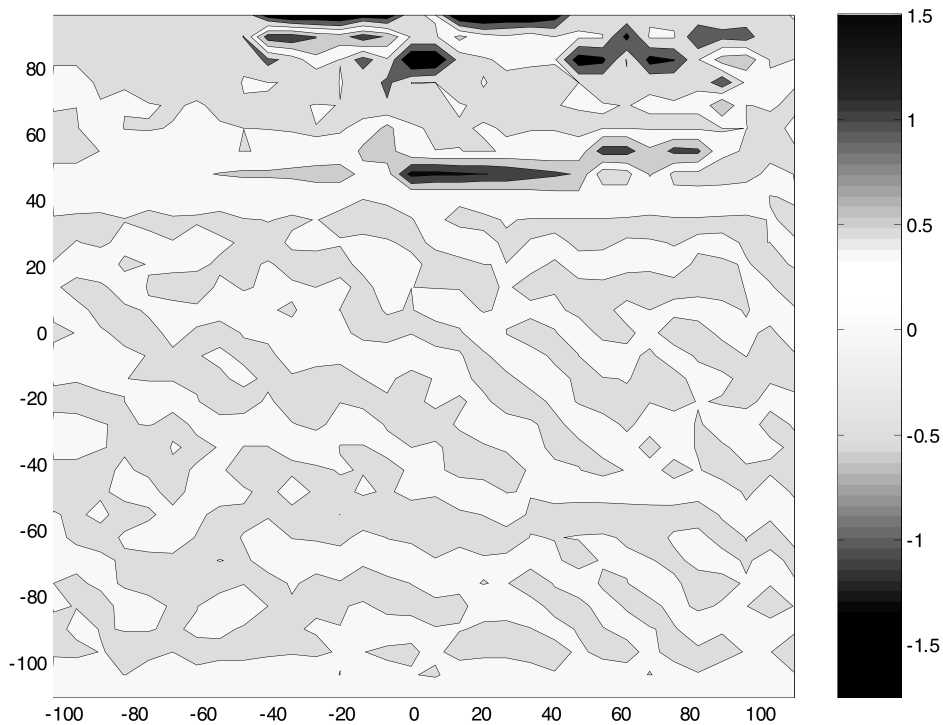

Figure 3. Strain in a layered snowpack shown to be concentrated at snow layer boundary between dense and less dense snow. Scale in snow is in mm. Scale on right is strain.

The loading experiments were conducted in a cold lab held at a constant -6° C. Most of the snow utilized in the experiments consisted of a layer or layers of sieved snow to achieve a uniform 2 mm grain size with harder (more resistant) and denser crusts composed of 0.5 to 1 mm round grains at the surface. The 2 mm grain size was chosen to minimize boundary influences by having the width and depth of the experiment 125 times larger than the grain size. Various iterations of snow layers were used to approximate different layered conditions in the snowpack. Images were taken at rates as slow as one frame per second and as fast as one frame per 0.06 seconds.

RESULTS

The results from preliminary experiments show that the load is more horizontally distributed in layers of snow that are harder and denser. A hard, dense layer of snow (315 kg/cm^3, pencil hard) approximately 0.05 m thick on top of 0.20 m of lower density (210 kg/cm^3, 1 finger hard) snow was loaded at the surface . Displacement caused by the loading plate was distributed horizontally across the harder, "bridged" layer at the surface (Figure 4). Strain was concentrated at the boundary between the hard dense layer and the less dense sieved snow (Figure 3). In a relatively homogenous snowpack, with snow grains sieved at 2 mm throughout the entire 0.25 m height of the box, the displacement occurred only underneath the loading plate and was not distributed horizontally (Figure 5).

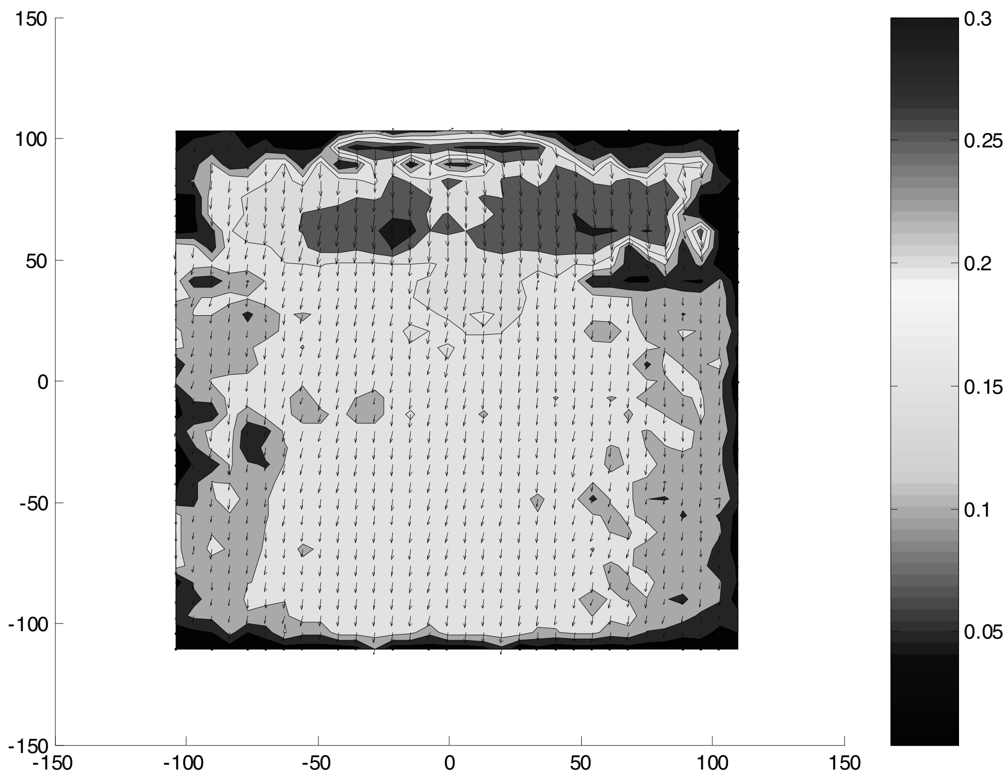

Figure 4. Displacement vectors in a hard slab layer over less dense snow. Note horizontal distribution of displacement beyond the loading plate at the top. Scale is in mm.

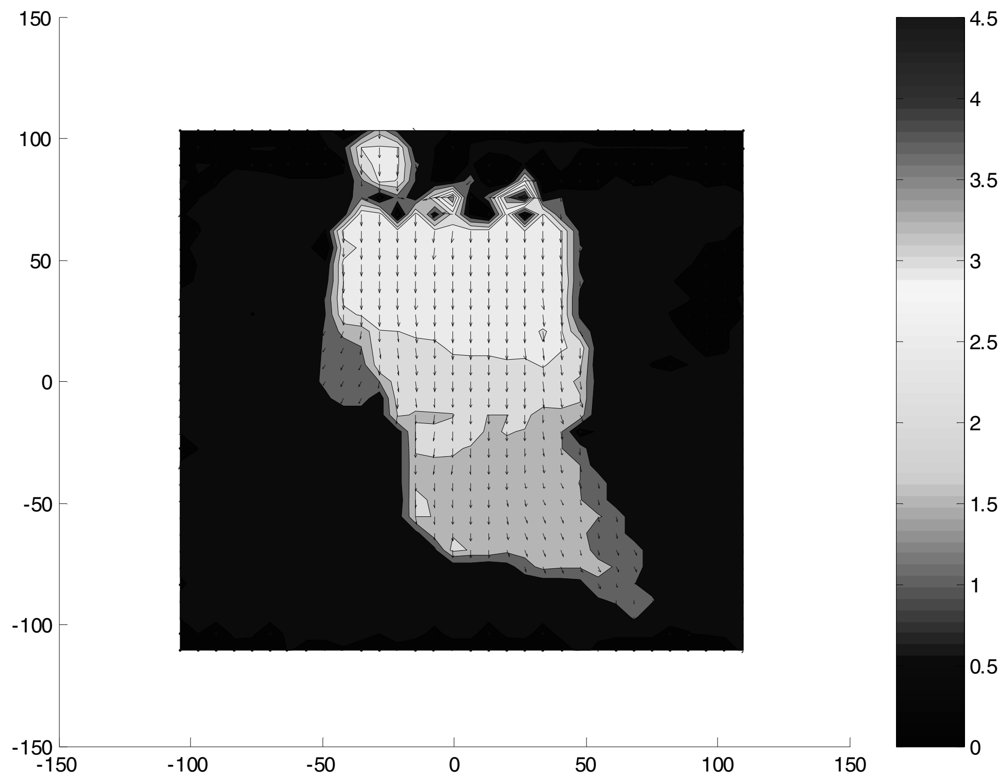

Figure 5. Displacement of a relatively uniform snowpack. Displacement occurs in vertical direction beneath the loading plate. Scale is in mm.

CONCLUSION

Particle image velocimetry is a practical technique to measure displacement and strain in snow underneath a band load. Snowpacks with hard layers distribute a band load horizontally compared with relatively uniform snowpacks which are displaced mostly in the vertical direction. This research is in the preliminary stages and more types of snow, including snow taken directly from a natural snowpack, need to be analyzed using the PIV technique. Further research will include varying the snow layers in density, crystal type and resistance (hardness) as well as varying the thickness of the harder, denser, bridged layer at the surface. Load cells will be placed beneath the snow and on the piston to measure stress and strain rate. I would also like to adapt this technique so that PIV could be used in the field to measure the strain beneath an actual skier or snow vehicle.

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REFERENCES

Brown, R. L., 1979: A volumetric constitutive law for snow subjected to large strains and strain rates, CRREL Report 79-20.

Fohn, P., 1987: The stability index and various triggering mechanisms, *IAHS* Publ. no. 162, 195-207.

Keane, R. D., and R. J. Adrian, 1992: Theory of cross-correlation analysis of PIV images, *Appl. Sci. Res.,* **49**, 191-215.

Schweizer, J., 1993: The influence of the layered character of snow cover on the triggering of slab avalanches, *Annals of Glaciology,* **18**.

Schweizer, J., and C. Camponovo, 2001: The skier's zone of influence in triggering slab avalanches, *Annals of Glaciology,* **32**, 314-320.

Shapiro, L. H., J. B. Johnson, M. Sturm and G. L. Blaisdell, 1997: Snow Mechanics, review of the state of knowledge and applications, CRREL Report 97-3.

Yosida, Z., et. al., 1956: Physical studies on deposited snow II. Mechanical properties (1), Contribution no. 307, Institute of low temperature science, Hokkaido Univ., Japan, **9**, 1-81.