EMPIRICAL ANALYSIS OF SNOW DEFORMATION BELOW PENETROMETER TIPS

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ABSTRACT: Recent field observations suggest that when an object, such as a digital snow penetrometer, is pushed through snow, a zone of densified snow develops in front of it. It is this zone of densified snow, rather than the actual tip of the object itself, that impacts on newly encountered snow as the object is pushed deeper into the snowpack. The concept of a compacted zone is introduced to describe this zone of snow. This is a sub-region of the broader deformation zone that encompasses all snow deformation below the tip of the penetrating object. The shape of both the deformation zone and compacted zone is influenced by the shape of the object's tip but also by the density, temperature, moisture content, grain size and grain shape of the snow through which the object is being pushed. The compacted zone effect is described and the impact on snow deformation of different snow densities and different tip shapes is preliminarily assessed. The use of particle image velocimetry in conjunction with a moving body coordinate system is presented as a useful tool for analysing deformation patterns for moving objects through uniform snow. The importance of this effect for penetrometer tip design and assessment of vertical resolution is discussed. Data is taken from a series of video and rapid-fire still camera shots of different shaped penetrometer tips being pushed through a clear, stiff plastic box filled with snow. Snow confinement along the side of the snow box is identified as a limitation of this technique.

KEYWORDS: snow deformation, penetrometer, compacted zone, snowpack stratigraphy

1. INTRODUCTION

This preliminary study reports on a method for studying the patterns of deformation ahead of a thin metal rod that is pushed through the snow. While these deformation patterns may be of interest to anyone who has pushed an avalanche probe, a ski pole or similar object into the snow, they are of particular importance to those studying high-resolution digital snow-sensing penetrometers. Such instruments typically measure certain snow properties (hardness, capacitance, light reflectivity or a combination of these) at a high frequency, at or near their tip as they are pushed through the snowpack. As such, an understanding of how snow deforms around the penetrometer tip is vital to understanding the true nature of the measurement being made by the instrument. Deformation patterns of snow under penetrating objects have been studied by several authors. Fukue (1977) deformed snow using both a blade shaped object and a flat plate. For the flat plate, his principle focus was on the difference in deformation patterns between slow deformation in the ductile range and rapid deformation where inter-grain bonds are broken. For the blade, he focussed on relationships between applied vertical stress and penetration depth and did not analyse the deformation patterns of the snow under the blade. Johnson and Schneebeli (1999) developed a micromechanical theory of penetration for a cone penetrometer and included terms to account for the impact of particle fragments in the compacted zone; however, no estimation of the extent of this zone was made. Various workers have analysed the strain response of snow to skier loading (e.g. Schweizer et al.,1995; McClung and Schweizer, 1999). van Herwijnen et al. (2005) used video capture and particle image velocimetry to quantify snow displacement during weak layer failure. Gleason (2005) also used this technique to measure strain in snow that was subjected to a load from a 25cm x 8cm plate.

In this study, we made use of video capture and particle image velocimetry and focus on small rod- and blade-style tips similar

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to those in use in high resolution penetrometers. Additionally, we focused primarily on steady state deformation patterns for a moving object which is a novel approach and especially pertinent to penetrometer design.

2. METHODS

Our method involved filming metal rods with different shaped tips being pushed through snow contained in a clear, stiff plastic snow box. The snow box that was used in this experiment measured 20cm x 35cm x 5cm (Figure 1). Two sides (one of the 20cm x 5cm sides and one of the 35cm x 5cm sides) were removable, which allowed the box to be easily filled with snow by pressing it into the snowpack, keeping the long dimension of the box parallel to the snow layers. The snow box was then carefully removed from the snowpack and excess snow scraped away from the sides. The exposed snow on the long side was seeded by sprinkling chilli flakes onto it before being covered with the clear, stiff plastic side that had previously been removed. The whole assembly was then placed upright with the long, seeded side vertical and facing the camera. In practice, horizontal terrain in deep snowpack areas was found to be most suitable for this experiment. Storm snow layers greater than 5cm thick were sought to keep the hardness and density as uniform as possible within the snow box.

As a metal rod was pushed into the snow, snow displacement was videoed through the snow box; this displacement was made more prominent by the chilli flake ‘seeds’ which contrasted with the surrounding snow. Videos were taken on two different days using three different video capturing devices. These were: a digital camcorder (recording at 30 frames per second); a digital camera used in ‘movie’ mode (15 frames per second); and a rapid-fire digital SLR camera (3 frames per second). The group of successive images for a particular run is referred to here as an image stack.

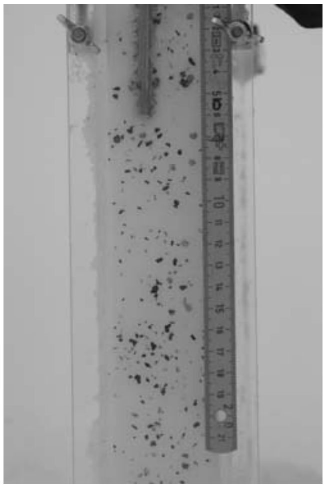

Figure 1. Snow box filled with snow and seeded with chilli flakes.

A total of 19 image stacks were recorded with three different shaped tips. Two of the tips were made from a 12 mm diameter brass rod, one rounded and the other conical with the angle at the tip subtending 90º. The third tip was a blade, 40 mm wide and 2 mm thick with a bevelled tip. The angle of the bevelled tip was approximately 90º. The density of the snow samples ranged from 38 kg m^{-3} to 333 kg m^{-3} and hand hardness values ranged from fist to pencil. The temperature of the snow ranged from 0ºC to -2.5ºC.

3. QUALITATIVE DESCRIPTION OF SNOW DEFORMATION

To describe the deformation patterns under the rod tip we introduce two terms: the deformation zone and the compacted zone (Figure 2). The deformation zone refers to the area of snow under the rod tip that shows a strain response to the movement of the rod. The term ‘compacted zone’ has been used in engineering geology in the study of the deformation of porous rocks (Leite and Ferland, 2001), which is quite analogous to deformation in snow. It refers to a specific area within the deformation zone directly beneath the tip where the density is approximately uniform; further densification in this zone proceeds slowly or not at all. The relatively dense snow in the compacted zone is able to transfer the stress from the rod tip to lower density snow on the other side of the compacted zone without itself undergoing significant extra densification. Within the compacted zone, snow grains slide past one another, their trajectories becoming more perpendicular to the direction of rod displacement the closer the particle is to the tip.

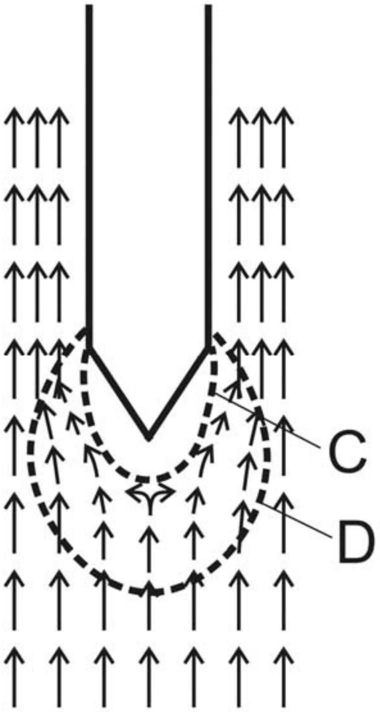

Figure 2. Schematic representation of the compacted zone, C, and the deformation zone, D. The arrows represent hypothetical velocity vectors of snow particles with velocity relative to the movement of the tip. Imagine that the rod is stationary and the snow is moving upwards to meet it.

From the image stacks, it was evident that fairly sizeable deformation zones developed beneath both the rounded and conical tip for all snow densities. By comparison, the deformation zone around the blade was much smaller. Particles at the leading edge of the deformation zone appeared to move closer together implying that densification was taking place at this point. As the tip moved closer to these particles, they started to move sideways away from the vertical axis of the tip. Most snow particles were deflected away without ever contacting the tip itself. The snow that was immediately under the tip was seen to move at a very similar speed to the tip itself. Much of the snow in this region travelled for quite a distance, trapped directly beneath the tip. This observation supports the idea that there is an area here that is of special interest, namely the compacted zone. For the rounded and conical tips, some slow movement of the snow particles within the compacted zone relative to the overall displacement of the zone was visible in the image stacks. For the blade tip, at the resolution of the camera used, it was not possible to distinguish the compacted zone from the deformation zone.

For homogeneous snow, with rod penetration proceeding from an undisturbed snow surface, deformation of snow under the metal rod can be divided into two phases. These are an initial phase where snow under the rod is densifying and the deformation and compacted zones are expanding in size, and a stable state phase where the deformation and compacted zones are constant.

For two of the pushes through very low density snow, a stop-start, ratcheting effect (Yosida, 1963) was seen, characterised by successive periods of static densification and rapid advance of the deformation zone. This effect was likely the result of the snow samples being moist, which caused adhesion of the grains through capillary action. The snow temperature for these runs was 0ºC and -0.5ºC respectively.

4. MEASUREMENTS OF SNOW DEFORMATION

4.1 Visual inspection

Manual measurements of the vertical and horizontal extent of the deformation zone during the steady state phase were made for all image stacks by toggling between a pair of frames in the stack and visually estimating the furthest particle movement from the rod tip. This was repeated for at least 20 frame pairs in each image stack and mean values calculated.

Figure 3 shows the mean vertical extent of the deformation zone for different tip shapes and different snow densities. The blade shaped tips showed substantially less deformation than the conical and rounded tip shapes. In all cases except one, the conical shaped tip showed less deformation than the rounded tip for the equivalent snow density. It is interesting to note that for some of the low density measurements, the vertical extent of the deformation zone was substantially greater than for larger densities. In a similar argument to the ratcheting effect in the section 3, a high moisture content in these pushes is felt to have contributed to the increased deformation zone.

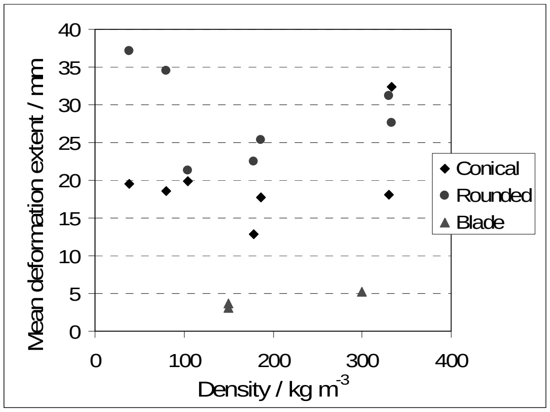

Figure 3. Mean vertical extent of the deformation zone for different snow densities and tip shapes.

Figure 4 shows the mean horizontal deformation for different snow densities and tip shapes. Again, the blade shape showed substantially less deformation than both the rounded and conical shaped tips. All tip shapes showed a gradual increase in the amount of deformation with increasing density, with the exception of the lowest density pushes for both the rounded and conical shaped tips.

4.2 Particle image velocimetry

Particle image velocimetry, e.g. Adrian (2005), is an optical technique typically used for tracking particles in a moving fluid. Gleason (2005) used this technique to measure strain in snow that was subjected to a load from a 25cm x 8cm plate. Our experimental setup was similar to that of Gleason although both our snow box and our penetrating objects (the different tips) were substantially smaller and our penetrating objects were driven into the snow by hand rather than by a hydraulic piston.

The captured video images were processed in such a way that the seeded particles showed up as white dots on a black background. The tracking software calculates a series of displacement vectors for each particle for successive image frame pairs. By dividing the displacement vectors by the time lapse between each frame, a velocity vector can be generated. If the time lapse between each frame becomes too large and the particle displacement nears half the average particle separation distance, particle tracking becomes problematic. This is because, by the second frame, particles other than the one being tracked will have moved close to the original particle's location causing confusion as to which the correct particle is. As a result of this, we found that particles could not be tracked well for the images captured at a rate of 3 frames per second.

To investigate the extent of deformation under the metal rods, it is convenient to consider a moving body coordinate system whose origin moves in a manner consistent with the tip of the penetrating rod. This allows us to analyse the movement of snow relative to the rod, and importantly generate composite images of displacement or velocity vectors from different frame pairs superimposed onto one image. These images essentially display the deformation patterns around the tip as if the tip was imagined to be stationary and the snow was 'flowing' around it. Figure 5a shows such a composite image of the displacement vectors for all frame pairs of an image stack for a push through 330 kg m^{-3} pencil-hard snow and Figure 5b is an interpretation of the deformation patterns. From this interpretation, the vertical extent of the deformation zone is approximately 36 mm which is a little higher than the manually measured value of 31.3 mm for this image stack. The vertical extent of the compacted zone was estimated to be 26mm for this image. The horizontal deformation from this image can be seen to be one-sided, measuring about 10 mm on the right hand side and 20 mm on the left. The mean of these two

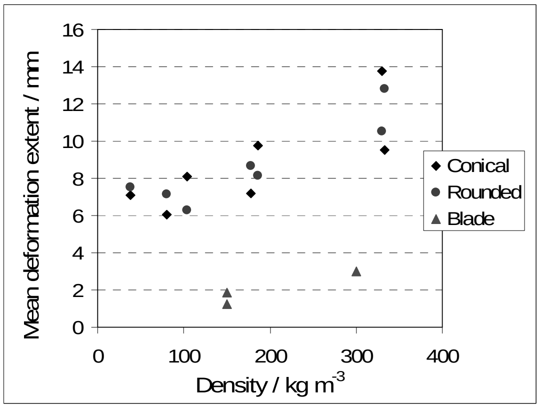

Figure 4. Mean horizontal extent of deformation zone for different snow densities and tip shapes.

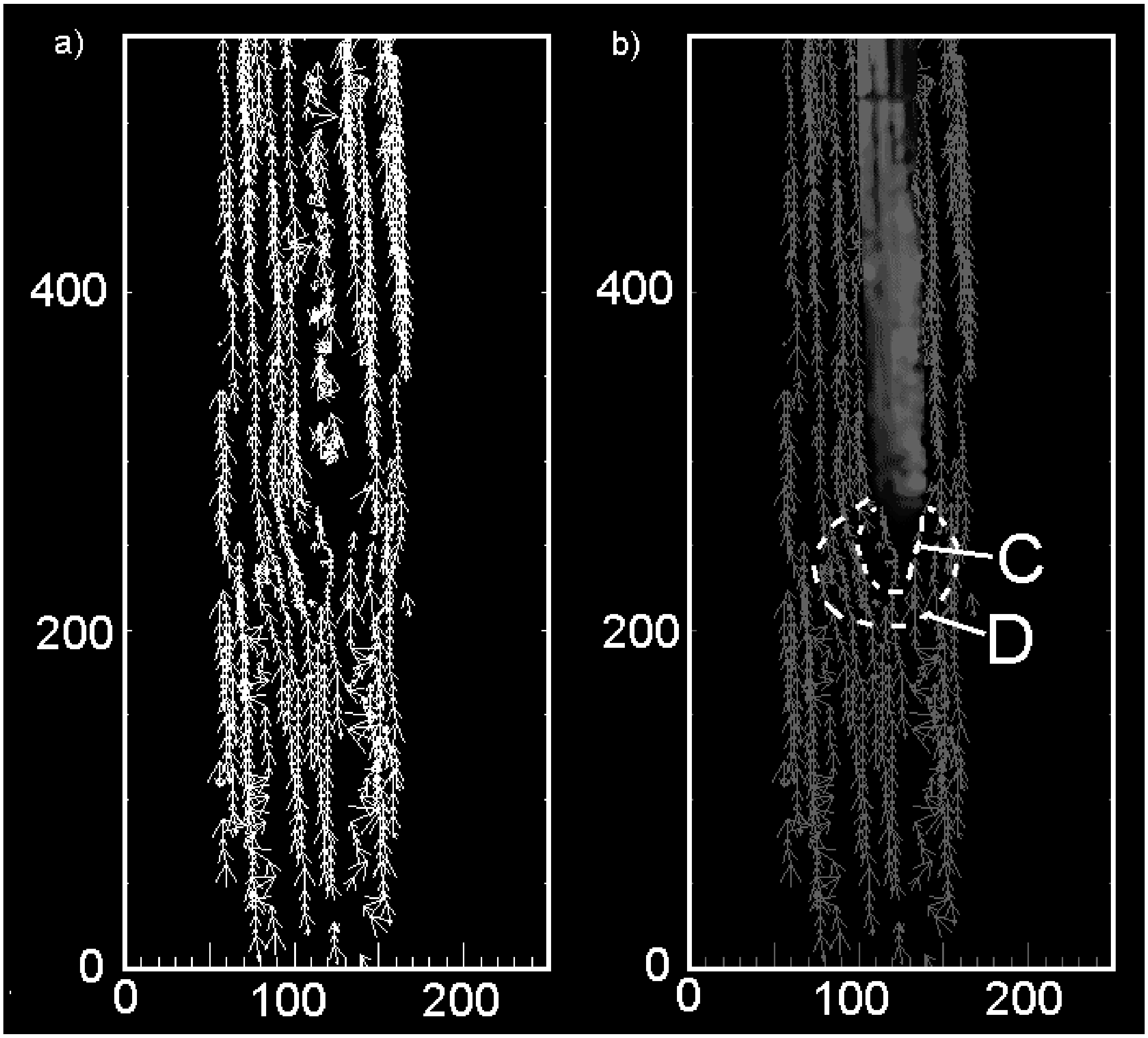

Figure 5. a) Composite image of displacement vectors for all frame pairs for an image stack for a rounded tip pushed through snow with a density of 330 kg m-3. Scale is in pixels, 1 pixel = 0.61 mm. b) Interpretation of the compaction zone, C and the deformation

values is 15 mm which is also slightly higher than the manually measured value of 12.8 mm.

5. DISCUSSION

For the design of a force-resistance penetrometer tip, it is desirable to minimise the extent of the deformation zone that develops ahead of the penetrometer sensor. This could be achieved by simply making as small a tip as possible. However, if the tip becomes too small, the penetrometer measures the rupture of individual snow grains, rather than the desired bulk property of snow hardness. Therefore, we seek a compromise; we want to break sufficient bonds to be confident that we are measuring the bulk snow hardness property but with the minimum of snow deformation occurring beneath the penetrometer tip. To this extent, it might appear that a blade tip shape should be the optimum design. However, our experience with blade shaped tips on a Sabre penetrometer encountered problems. For narrow blades, the force response was insufficient to generate a response from the load cell sensor. For wider blades that presented a sufficient surface area to generate a measurable force, a signal that was somehow jerky but at the same time damped was observed. This was attributed to poor balance of the wide blade while being pushed through the snow. This problem could possibly be resolved by using a narrow blade with a more sensitive load cell.

The importance of the compacted zone in snow deformation studies is that it forms a load path between the tip and the surrounding lower-density snow. This has two implications for force-resistance penetrometers. First, the location of applied force moves ahead of the tip. Second, if the compacted zone is large, the applied force may act over a greater vertical extent than is desired. The latter is important as it may reduce the vertical resolution of a penetrometer. Furthermore, in a varied snowpack, the size of the compacted zone and therefore the vertical resolution of the instrument may change as different snow layers are encountered.

During the analysis, it was found that the deformation zone was easier to identify than the compacted zone. For the thin blade tip, it was sometimes impossible to distinguish between the deformation zone and the compacted zone. Where this is the case, the importance of the compacted zone diminishes, since the disparity between the shape of the tip and the shape of the compacted zone becomes minimal.

A major limitation of this technique is that the side of the snow box creates a boundary condition. Snow that would have otherwise been displaced perpendicular to the side of the snow box and outwards towards the viewer is redirected and instead moves away parallel to the side of the snow box. This effect is likely to result in an overestimation of the size of the deformation and compaction zones. Other limitations include a tendency for some particles to adhere to the side of the snow box and the inability of the particle tracking software to track particles that are too close to each other.

6. CONCLUSIONS

Video capture of snow displacement using a snow box and particle image velocimetry is a practical technique for analysing deformation patterns beneath small rod tips. The following points were noted:

- Deformation zones set up under a penetrating rod can extend some distance below the rod’s tip. Vertical extents of between 27 mm and 31 mm below the bottom of the tip were measured for a rounded tip pushed through snow with a density of 330 kg m^{-3}.
- The extent of the deformation zone (and compacted zone) was affected by the shape of the tip.
- Thin, blade-like tip designs gave rise to very small deformation zones. This leads to a conjecture that the vertical extent of the deformation zone is controlled principally by the maximum width of the penetrating object.
- Empirical relations between the deformation zone extent and snow density and hand hardness are preliminary and not assessed statistically. We are certain that all the variance of the system has not been captured and interrelationships between these and other variables not fully explored.
- The concept of a compacted zone, where density is approximately constant is introduced for the region directly beneath the tip. Snow particles in this zone move slowly relative to the tip.

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8. REFERENCES

Adrian, R.J. 2005. Twenty years of particle image velocimetry. *Experiments in Fluids, 39*, 159-169.

Fukue, M. 1977. Mechanical performance of snow under loading. PhD thesis. *McGill University.*

Gleason, J.A. 2005. Particle image velocimetry; a new technique to measure strain in loaded snow. *Proceedings of the 2004 International Snow Science Workshop, Jackson Hole, Wyoming.*

Johnson, J.B. & Schneebeli, M. 1999. Characterizing the microstructural and micromechanical properties of snow. *Cold Regions Science and Technology, 30(1-3)*, 91-100

Leite, M.H. & Ferland, F. 2001. Determination of unconfined compressive strength and Young's modulus of porous materials by indentation tests. *Engineering Geology, 59*, 267-280.

McClung, D.M. & Schweizer, J. 1999. Skier triggering, snow temperatures and the stability index for dry-slab avalanche initiation. *Journal of Glaciology, 45*, 190-200.

Schweizer, J.; Schneebeli, M.; Fierz, C. & Fohn, P.M.B. 1995. Snow mechanics and avalanche formation: field experiments on the dynamic response of the snow cover. *Surveys in Geophysics, 16*, 621-633.

van Herwijnen, A.; Jamieson, B.; Schweizer, J. & Naaim-Bouvet, F. 2005. High-speed photography of fractures in weak snowpack layers. *Cold Regions Science and Technology, 43*, 71-82.

Yosida, Z., 1963. Physical Properties of Snow, In Ice and Snow: Properties, Processes and Applications, Edited by W.D. Kingery, M.I.T. Press, Mass., 485-527.