AXISYMMETRIC MEASUREMENTS OF EXTENDED DEFORMATION AROUND THE SNOW MICROPENETROMETER TIP

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ABSTRACT: Current physical models for the snow micropenetrometer (SMP) make the assumption that the tip of the SMP probe only stresses or fractures the ice grains that it contacts directly. However, past research indicates the existence of an extended deformation zone around the tip which contains many deformed or fractured ice grains. A semicylindrical SMP probe was machined for the purpose of this experiment. It was placed with its flat side against a plexiglass window and driven into well rounded snow using the SMP. The ensuing axisymmetric deformation was monitored using an optical strain measurement system. Results confirm the existence of a deformation zone ahead of the tip of the SMP probe. This zone had a visible area of 98 to 141 mm\(^2\). Estimated calculated volume of the deformation zone was on the order of 1000 mm\(^3\), potentially containing hundreds or thousands of grains.

KEYWORDS: Snow micropenetrometer, strain, compaction

1. INTRODUCTION

Accurate interpretation of snowpack stratigraphy is critical to avalanche forecasting. Digital cone penetrometers, most popularly the Snow Micro Penetrometer (SMP), have been developed to this end (Schneebeli et al, 1998). Force measurements taken at the tip of the SMP probe give indication of the properties of snow, which are interpreted through either empirical or physically-based models (Johnson and Schneebeli, 1999; Marshall and Johnson, 2009; Loewe and van Herwijnen, 2011). Physical theories have traditionally neglected compaction of snow grains around the tip of the SMP probe (e.g. Johnson and Schneebeli, 1999), arguing that the low density of snow makes compaction negligible. A theory for snow compaction around the penetrometer tip neglects compaction ahead of the tip and assumes compaction only exists to the side (Johnson, 2003). However, previous work has revealed the existence of a compaction zone ahead of the tip of probes of various shapes driven through snow (Floyer and Jamieson, 2006 and 2010; van Herwijnen, 2012; Riche and Schneebeli, 2010). This paper describes a series of experiments designed to directly observe and measure the compaction zone around a split-axis SMP probe model tip using ARAMIS, a high-resolution optical strain measurement system using particle image velocimetry (PIV).

2. EXPERIMENTAL PROCEDURE

An experiment was designed to measure the deformation zone ahead of a split-axis replica SMP tip. Given the shape of the tip, it was assumed that an axisymmetric deformation condition exists in snow around the SMP probe (Floyer, 2008), and therefore deformation in the radial direction could be directly observed through penetration of a split-axis probe through snow. A split-axis probe, with dimensions equivalent to the SMP probe and tip was used (Figure 1). The flat side of the probe was placed against a window grains that had been left to sinter overnight in a -15°C cold room.

Strain was measured using ARAMIS, a commercial optical deformation analysis system created by GOM industries (http://www.gom.com/).
Figure 1: Front and side views of split-axis SMP probe used for the experiment. The probe was speckled with paint to allow movement tracking with ARAMIS.

It uses noncontact optical measurements to determine parameters such as material coordinates, displacements, speed, acceleration, strain, strain rate and material characteristics during loading. Strain ranging from 0.05% to over 100% can be measured. Strain is calculated using a particle image velocimetry algorithm to track the displacement of patterns in the images. For our experiments, small specks of paint on the side of the snow sample were used as tracking points. The software calculates strain in moving windows, i.e. square groups of pixels. By tracking the movement of each speck of paint, the software calculates the 2D strain in each window. Images were 2448x2050 pixels and had a spatial resolution of 0.08 mm/pixel. Images were recorded at 15 frames per second. Resulting minor principal strain was analyzed. Minor principal strain is the maximum compressive strain at a given location and was therefore deemed the best parameter for defining a deformation zone. Additionally, the principal directions associated with the maximum compressive strains were calculated.

The strain fields contained some noise. A noise threshold was established for each image series by noting the highest magnitude of minor principal strain calculated before penetration. Noise thresholds were always below 1%, but did vary from test to test.

ARAMIS is unable to track rigid body motion of individual grains; rather it calculates relative motion between specks of paint to find strain. Since a continuum approximation is necessary to calculate macroscopic strain, excessive rigid body motion of individual grains can create invalid deformation patterns where the continuum approximation is no longer valid. Strain then becomes incalculable.

2.1 Deformation zone size parameters and processing

The deformation zone was characterized by its total area, width at the level of the widest part of the SMP tip, and length ahead of the tip (Figure 2).

Specifically, the deformation area, \( A \), was defined as the area \( (\text{mm}^2) \) ahead of the widest part of the tip that displayed strain greater than the noise threshold (Table 1). Presumably, this is the area where snow deformation could affect the force reading since the SMP tip is attached to a force sensor. To calculate the area of the deformation zone, a color plot overlay showing the maximum compressive strain was binarized to show the deformation zone in white and undeformed snow in black. Then, based on the known location of the SMP probe tip, the compacted area ahead of the widest part of the tip is calculated by counting the white pixels and multiplying by the area per pixel.

The height, \( H \), of the deformation zone was measured as the distance \( (\text{mm}) \) directly beneath the SMP tip that displayed maximum compressive strain greater than the noise threshold. ARAMIS is able to track a known point on the probe that is a known distance above the tip. In this way, the position of the tip is known in all images. Then, a MATLAB script scans the strain data directly beneath the tip until strain below the noise threshold is found. The vertical distance from this point to the tip is calculated as \( H \).
The width, W, was measured as the sum of the horizontal distances (mm) left and right of the widest part of the SMP tip that displayed maximum compressive strain greater than the noise threshold. As shown in Figure 2,

\[ W = W_1 + W_2 \] (1)

To calculate the width of the deformation zone automatically, the widest part of the penetrometer cone tip is located in each image. The MATLAB script then scans that row of pixels to count pixels until a strain value below the noise threshold is encountered. Total counted pixels are multiplied by scale (mm/pixel) to calculate W.

3. RESULTS

3.1 Snow Properties

Eight tests were performed in dry sintered snow using the split-axis probe with a penetration rate of 20 mm/s in a -15°C cold room.

Tests 1-4 were performed in snow with a density of 203 kg/m³ and tests 5-8 were performed in snow with a density of 257 kg/m³. In both sets of tests, average grain size was 0.5-1.0 mm.

The strain plots qualitatively show zones of deformation around the SMP tip. Each image typically exhibited a zone immediately surrounding the tip where deformation due to rigid body motion exceeded ARAMIS’s ability to calculate strain. This region of high deformation suggests the existence of a compacted zone containing broken particles, as described by Floyer (2006). Around the highly deformed zone, there was a zone showing measurable strain which diminished with distance from the SMP tip. Figure 3 shows an example of the deformation zone from test 2. The area with the contoured overlay represents areas with calculable strain; all other areas experienced such high deformation that strain was incalculable.

3.2 Deformation Zone Height

There was no consistent trend in the height of the deformation zone with penetration depth (not shown). On average, in our experiments H ranged from 3.7 to 5.4 mm (Table 1).

3.3 Deformation Zone Width

The width of the deformation zone was generally greater than the height. Width in tests 2, 4, and 6 increased for the first 15 to 30 mm of penetration, then decreased and reached a steady state value (see results of sample 2 in Figure 4). Width in tests 1, 4, 5, 7, and 8 increased and then reached steady state value without peaking first (see results of sample 8 in Figure 5). Steady state values of width were similar in other tests as well. On average, W ranged from 15.1 to 18.0 mm (Table 1).

Figure 3: Contour plot of maximum compressive strain overlaid on image of SMP tip through snow. Images consistently showed a highly deformed zone, presumably compacted through bond breakage and grain realignment, surrounded by gradually decreasing measurable strain. Note that negative strain denotes compression. Area with no strain overlay (grayscale) was too deformed for quantification of strain.
3.4 Deformation zone area

As for the width of the deformation zone, the area of the deformation zone generally increased in one of two patterns. For tests 1, 2, 4, and 6, the area of the deformation zone increased for the first 15 to 30 mm of penetration, then decreased and reached a steady state. As an example, a plot of deformation zone area as a function of penetration depth is shown in Figure 6. For tests 3, 5, 7 and 8, the area of the deformation zone increased and reached steady state without a noticeable peak, such as that shown in Figure 7. In all tests, mean area was between 98 and 141 mm$^2$ (Table 1).

3.5 Deformation zone volume

By assuming an axisymmetric strain condition, the volume of a full cylindrical SMP deformation zone can be estimated by an integral in polar coordinates based on the deformation zone area:

$$V = \int_A \int_0^\pi dA r d\theta$$

(2)

where $dA$ is a differential area, $r$ is the distance from probe’s symmetry axis to the differential area, and $\theta$ is rotation angle about the axis. By taking each pixel in the image to be a differential area, the volume represented by a pixel is:

$$V_{pixel} = A_{pixel} r \pi$$

(3)

The volumes represented by each pixel, when added, comprise the estimated deformation zone volume. Estimated volumes are given in Table 1. In general, volumes were on the order of 1000 mm$^3$. Given the ~1mm grain size in this experiment, deformation zone volume estimates suggest that quantities on the order of 1000 snow grains could be entrained in the deformation zone.

3.6 Compressive strain direction

Maximum compressive strain was approximately normal to the SMP probe tip, indicating that the tip is the cause of deformation.

4. CONCLUSIONS

Results confirm the existence of a deformation zone that extends a significant distance to the side and ahead of the SMP tip, as seen in similar experiments (Floyer and Jamieson, 2010; van Herwijnen, 2012; Riche and Schneebeli, 2010). In general, $W$ was about 3 times the width of the SMP tip. $H$ was about equal to the height of the tip. Total deformation zone area was about 10 times the area of the SMP tip.

Any strain ahead of the tip will result in force feedback to the SMP tip; therefore any physical model used to interpret SMP force signals must account for this force or demonstrate it to be negligible.

The high variability in the size of the deformation zone between sequential images suggests abrupt changes in snow structure as the probe penetrates the snow. These abrupt changes could be caused by the breaking of individual bonds. It is also

<table>
<thead>
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<th>Test</th>
<th>Snow Properties</th>
<th>Noise Threshold</th>
<th>Mean Height(H) (mm)</th>
<th>Mean Width(W) (mm)</th>
<th>Mean Area (mm$^2$)</th>
<th>Estimated Volume (mm$^3$)</th>
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<tr>
<td>1</td>
<td>200 kg/m$^3$ 0.5-1mm grain size</td>
<td>1.0%</td>
<td>5.3</td>
<td>16.8</td>
<td>117</td>
<td>1584</td>
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<td>1.0%</td>
<td>4.7</td>
<td>15.1</td>
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<td>1277</td>
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<tr>
<td>3</td>
<td></td>
<td>0.6%</td>
<td>5.4</td>
<td>18.0</td>
<td>141</td>
<td>2012</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.6%</td>
<td>4.3</td>
<td>15.8</td>
<td>104</td>
<td>1416</td>
</tr>
<tr>
<td>5</td>
<td>260 kg/m$^3$ 0.5-1mm grain size</td>
<td>1.0%</td>
<td>5.3</td>
<td>17.0</td>
<td>124</td>
<td>1730</td>
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<tr>
<td>6</td>
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<tr>
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<td>4.2</td>
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<tr>
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<td>3.7</td>
<td>16.4</td>
<td>98</td>
<td>1277</td>
</tr>
</tbody>
</table>

Table 1: Summary of deformation zone mean dimensions for all tests.
possible that the force chains which transmit load between grains are fluctuating abruptly, leading to rapid variation in strain patterns. This phenomenon has been shown to occur in dynamic granular systems (Liu and Nagel, 1992).

One remaining question is what portion of the deformation zone is created by the tip (and therefore registers force feedback from the SMP) and what portion of the zone is created by the rest of the probe and therefore does not influence force measurement. A rigorous understanding of what portion of the compacted zone influences SMP force reading will be necessary before any new physical force feedback theory can account for effects of compaction. A split-axis SMP probe with force sensor could be helpful to determine the exact extent of tip-influencing snow, as could numerical experiments using the finite element or discrete element method.

5. ACKNOWLEDGEMENT

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6. REFERENCES


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