Cone Penetration Testing (CPT): a valuable tool for investigating polar snow

Adrian McCallum

University of the Sunshine Coast, Locked Bag 4, Maroochydore DC, Queensland 4558, Australia. Corresponding author: amccallu@usc.edu.au

Abstract

Penetrative testing is the best means of assessing snow strength in situ. However, in hard polar firn, existing snow penetrative equipment is unable to penetrate at a constant rate to substantial depth. Therefore, existing Cone Penetration Test (CPT) equipment, typically used in soils, was modified to allow efficient testing in snow. Tractor-mounted hydraulically powered CPT equipment enabled rapid testing to depths of 10 m, in polar firn as hard as 10 MPa; data recorded included cone tip resistance and sleeve friction. Analysis of results suggests that three main determinants of snow's physical behaviour: its strength, density, and microstructure, can potentially all be obtained via this one test – the CPT.

Keywords

Cone penetration test, CPT, snow strength, snow density, snow microstructure, sleeve friction, polar firn, in situ testing

Introduction

Investigation of the physical properties of snow packs is of interest to researchers for many reasons, such as assessing avalanche potential or for estimating the load-bearing capacity of snow pavements. Whilst Abele and Gow (1975) outline three methods of strength assessment: surface load tests, sample testing and probing, only probing provides a time and cost-effective in situ means of assessment. Previous workers (Bradley, 1968; Dowd and Brown, 1986; Mackenzie and Payten, 2002; Schneebeli and Johnson, 1998) have used light-weight cone penetrometers to profile surface layers of snow packs, but this paper describes the first use of a hydraulically-driven system that is robust and powerful enough to reach depths of 10 m or more in hard polar firn.

The Cone Penetration Test (CPT) was developed in the Netherlands in the 1930s (Brouwer, 2007) for soil profiling, and for deriving soil properties such as density, shear strength, angle of internal friction and cohesion. The CPT evolved over time, incorporating a sensor for measuring sleeve friction in the 1950s, before an electric cone capable of measuring cone resistance and sleeve friction continuously was developed in the 1960s (Schaap and Fohn, 1987). The three primary CPT sensors record tip resistance \((q_c)\), sleeve friction \((f_s)\) and pore pressure \((u)\).

Tip resistance \((q_c)\) is the axial force acting on the 35.6 mm diameter cone tip, divided by the projected area of this cone (see Fig. 1). Sleeve friction \((f_s)\) is the frictional force acting on the friction sleeve, divided by the surface area of the friction sleeve (see Fig. 1). Pore pressure \((u)\) is the pore pressure generated during penetration (where there is free water), measured by a pore pressure sensor: \(u_1\) when measured on the cone, \(u_2\) when measured just behind the cone and \(u_3\) when measured just
behind the friction sleeve. Data from these sensors is collected simultaneously in real time, and CPT can used to estimate many physical soil parameters including undrained shear strength, soil friction angle, soil stress history, lateral stress, total density, relative density and void ratio, constrained modulus and additional parameters. 

Snow strength is controlled by the size of the bonds between grains (Colbeck, 1998). This depends on the microstructure of the snow: the bonds formed between grains by sintering that generally grow with time, giving strength to the bonded matrix of particles. It is the strength provided by this bonded microstructural matrix and not density that will account for snow's mechanical behaviour. An increase in density may suggest increased bonding and therefore greater strength, but dense snow can still exist in an unbonded state, so density alone is not an adequate proxy for snow strength. This paper examines the use of modified CPT equipment in polar snow, where for the first time, tip resistance, sleeve friction and pore pressure were simultaneously recorded. This paper does not examine test technique or CPT interpretation at length; these are examined elsewhere (McCallum, 2012, 2013). However, typical data from CPT are examined, suggesting that three major descriptors of snow's physical state – its shear strength, density and relative microstructure, may all be rapidly estimated to depth, using CPT.

**Method**

CPT equipment is typically mounted on a heavy truck or trailer-rig, primarily to ensure that sufficient reaction force can be provided when driving into hard soils. However, equipment modified for use in snow needs to be relatively lightweight, transportable and modular in nature. Therefore, in conjunction with Lankelma and Gardline Geosciences, a ‘box’ was constructed in which existing CPT equipment could be mounted and transported. The box provided a rigid frame for mounting hydraulic rams and was designed to attach to the three-point hitch of a standard agricultural tractor, such as those used by the British Antarctic Survey. The box (designated UK11), measuring 1.7 m × 1.45 m × 1.35 m and weighing approximately 1300 kg when loaded, can be seen in Figure 2.
attached to the back of a British Antarctic Survey tractor.

The hardness of the material through which a driven cone can penetrate depends on the reaction-force available from the pushing equipment. Because UK11 weighs only 1300 kg and a standard tractor three-point linkage only provides resistance to a downward, not an upward force, an additional rigid-link was used to provide increased resistance between the base of UK11 and the top hitch of the tractor. During use, the rigid-link could be left attached at the tractor, and then unscrewed and ‘trailed’ between subsequent testing sites. The maximum resistance offered by UK11 with the rigid-link in place was approximately 40 MPa, equivalent to a 4 tonne reaction force. The rigid-link can be seen in place in Figure 2.

The hydraulic ‘basement’ rams used to provide downward penetration of the cone had a stroke of 500 mm, a bore diameter of 70 mm, and were controlled via a two-way non-friction-controlled hydraulic lever, mounted to the underside of a workbench within the box. Gardline Geosciences provided four 35.6 mm diameter scientific cones from Geopoint Systems BV. The cones measured resistance on the cone tip, friction on the cone sleeve, and also had the capacity to measure pore pressure. Although possibly useful for assessing free-water within alpine snow, in the dry Antarctic firn tested, no pore pressure readings were obtained. Specifications for these cones are in Table 1 and a cone incorporating tip and friction sleeve is shown in Figure 1.

A Sick Stegmann wire-draw mechanism and incremental rotary depth encoder attached to the hydraulic rams was used to record cone depth to an accuracy of 5 mm. Data were recorded using a modified A.P. van den Berg ‘Golog’ data recorder, and a Panasonic C32 Toughbook laptop computer running A.P. van den Berg’s GOnsite! (van den Berg, 2002) windows-based software was used to manage CPT data acquisition and initial data manipulation.

<table>
<thead>
<tr>
<th>Table 1 – GeoPoint ‘Antarctic’ cone specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Specifications</strong></td>
</tr>
<tr>
<td>Cone Tip Section Area</td>
</tr>
<tr>
<td>Friction Sleeve Surface</td>
</tr>
<tr>
<td>Total Length</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Current Source</td>
</tr>
<tr>
<td>Working Temperature</td>
</tr>
<tr>
<td>Storage Temperature</td>
</tr>
<tr>
<td>Connector</td>
</tr>
<tr>
<td><strong>Tip Resistance</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>Maximum Load</td>
</tr>
<tr>
<td>Cone Area Ratio</td>
</tr>
<tr>
<td><strong>Sleeve Friction</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>Maximum Load</td>
</tr>
<tr>
<td>Sleeve Area Ratio</td>
</tr>
<tr>
<td><strong>Pore Pressure</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>Maximum Load</td>
</tr>
<tr>
<td>Filter position</td>
</tr>
<tr>
<td><strong>Inclination</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
</tbody>
</table>

The standard penetration rate was 20 mm s⁻¹ and a test to 5 m depth would take
approximately 5 minutes. Numerous tests could be conducted in quick succession, with moving the tractor taking the greatest amount of time. The CPT equipment performed largely without fault in challenging operating conditions at temperatures below –20°C. In order to standardise testing, only one cone was used. However, it was damaged due to experimental use within sea ice, so a second cone was then used. Two manufactured flat alloy plates of diameters 36 mm and 120 mm were occasionally used in place of conical tips for comparative testing.

After shipping the equipment to Antarctica by sea, almost one hundred cone penetration tests, typically to 5 m depth, were conducted at various locations within the vicinity of the British Antarctic Survey’s Halley V Research Station over the period 21 January to 22 February 2010. Figure 3 shows the Halley V Station site with test locations noted; roads to outlying areas are also shown.

Although summer temperatures sometimes exceed 0°C, the mean temperature at Halley is –30°C and annual snow accumulation is approximately 1.2 m. Tests were conducted as weather and operational commitments allowed, and were designed to investigate numerous factors, but particularly whether snow strength, density and microstructure could be estimated using CPT.

Results
This paper does not present all data obtained during testing. Representative data are presented to demonstrate the efficacy of the CPT process and the parameters that can be extracted from this testing. Elaboration on results and interpretation can be found in

Figure 3 – Aerial photograph of Halley V Research Station. The test area where most CPTs were conducted is shown, along with Station buildings and the vehicle park. Roads to outlying areas are also shown.
McCallum (2012) (Chapters 5 and 7) and McCallum (2013). The majority of testing was conducted to a depth of ~ 5 m, or until excess vibration caused early termination of the test. Penetration rates were varied, and cone tip resistance (MPa) and sleeve friction (MPa) were recorded for each test. Except for a number of anomalous situations, no pore pressure readings (kPa) were obtained.

Data for snow pit #1, including stratigraphy, density, grain size, hardness and snow type, is presented in Figure 4, generated using SnowPilot (Chabot and Kahrl, 2009). SnowPilot’s data fields are consistent with the guidelines published within “Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States” (American Avalanche Association, 2004).

All tip resistance data for a standard cone, obtained within 1 m of a snow test pit, are shown in Figure 5. Tests were conducted at different rates; the average data for each location is shown as a bold black line.

Initial examination of Figure 5 reveals a drop in resistance every ~ 0.5 m where rods are changed, a high degree of consistency between

![Figure 4 – Snow Pit #1 data showing layer hardness, crystal type, grain size and density.](image-url)
tests, and qualitative indication of variation in snow hardness. Icy layers observed within the snow pit are evident in the resistance data at ∼1.7 m, 3.8 m and 4.7 m. Note that tip resistance lags behind layer transitions because the cone must penetrate into the layer by an amount described as the ‘critical depth’ (De Beer, 1963) before actual layer resistance is measured. Work by Pielmeier and Schneebeli (2003) and Bellaire et al. (2009) suggest that in my work conducted at Halley, the ‘critical depth’ may equal ∼25 mm. Therefore, the tip resistance trace is constantly varying and full layer resistance is rarely achieved because layer thicknesses are typically less than this amount. Analysis of CPT data to derive snow physical properties is discussed next.

**Discussion**

**Snow strength from Cone Penetration Tests**

A conceptual physical model of snow penetration was developed to enable estimation of snow shear strength from CPT resistance data. As a cone is driven through an (assumed) bonded matrix of snow, two things must occur to allow its progress:

![Image of CPT data showing tests conducted adjacent to snow test pit #1. The bold black line represents the mean resistance value generated from all tests.](image-url)
1) firstly, the bonds linking grains within the snow must be broken, then
2) the fractured material must be displaced and compacted into the snow surrounding the cone.

In terms of the Mohr-Coulomb criterion ($\tau = C + N \tan \Phi$, where $\tau$ is shear strength, $C$ is cohesion, $N$ is applied normal stress and $\Phi$ is the friction angle of the material), firstly, the cohesion of the snow is overcome and then a frictional process occurs as fragments are compacted under (unknown) confinement, a process analogous to semi-confined compression testing of snow. In the case of the standard 35.6 mm, 60° cone, compaction occurs out to a distance of $\sim 21$ mm; this is the maximum cone radius measured normal to the cone face (Fig. 6). Fractured particles are forced out from the cone tip, eventually into the annulus beyond the cone shoulder.

Fractured particles will be displaced normal to the cone face (Johnson, 2003). Some inclination will occur due to snow-cone friction, but this interaction is ignored because the frictional effect is an order of magnitude less than the normal forces acting on the cone. An equation of the form below is proposed to describe the sum of forces measured by the cone tip during penetration.

$$q_c = C_{vert} + S_{vert} + F_{vert}$$  \hspace{1cm} (1)

where $q_c$ is total tip resistance measured by CPT, $C_{vert}$ is the vertical component of cohesion (cohesion assumed equivalent to shear strength), $S_{vert}$ is the vertical component of the stress required to compact the snow (analogous to semi-confined compression testing), and $F_{vert}$ is the small frictional stress between the snow and the cone face (vertical component). This equation incorporates the simultaneous macroscopic contributions of cohesion from elastically stressed particles and compressive stresses owing to compaction of fractured material.

The cohesion value in equation 1 is a measure of snow shear strength, whereas resistance tests such as CPT are a measure of compressive strength (Mellor, 1972). Therefore, under uniaxial compression with limited confining stress, where the maximum shear stress ($\tau$) equals half the major principal stress ($\tau = \sigma_1 \sin45^\circ\cos45^\circ$), it is assumed that shear strength values used within equation 1 are multiplied by two to arrive at an estimate for compressive strength; and so when tip resistance is known, an equation such as equation 1 can be used to estimate snow shear strength.

The second term ($S_{vert}$) is a frictional-compactive term incorporating additional resistance due to compaction. Because specific volume is the reciprocal of density, Mellor (1975) states that any graph describing ‘a systematic relationship between pressure and density can be interpreted as an equation of state.’ Therefore, a measure of stress increase during compaction can be obtained by direct examination of published stress/density curves, such as those in Mellor (1975).

**Figure 6** – Possible strain path for fractured particles moving ahead of cone.
But, in attempting to deduce a stress increase via volumetric compaction, the deduced value depends on two interdependent unknowns: the final density after compaction and compacted volume. Final density after compaction was not measured, but one observation was made that can be used to define post-CPT compacted volume. After one test (Test 9), a portion of the snow surrounding the CPT hole was excised and the annulus thickness was measured to be \( \sim 2.2 \text{ mm} \) (Fig. 7), for snow of initial density \( \sim 450 \text{ kg m}^{-3} \).

This value can be used to define the final compacted volume, so then a final density and the stress required to effect this compaction can be obtained via data from Mellor (1975) or similar. A unitless pressure multiplier defining the stress increase can be obtained by the following equation:

\[
M = \frac{\sigma_{1(\rho_{\text{fin}})}}{\sigma_{1(\rho_{\text{init}})}}
\]

where \( \sigma_{1(\rho_{\text{fin}})} \) is the uniaxial compressive strength at the final density and \( \sigma_{1(\rho_{\text{init}})} \) is the uniaxial compressive strength at the initial density. This observation is consistent with work by Kartashov (1965) on the mechanical properties of snow and firn. He found via plate-testing that increasing the density of snow from \( \sim 450 \text{ kg m}^{-3} \) to \( \sim 590 \text{ kg m}^{-3} \) required an approximately five-fold increase in pressure. This method provides a means of estimating the stress increase across the range of volumetric compaction occurring at the cone tip during CPT.

The stress required to effect this compaction varies with initial density. Abele’s work (Abele, 1970) on the penetration of rigid plates into snow confirms that at the same penetration distance, the stress increase is greatest in higher density snow, and similarly, for the same applied pressure, settlement will decrease as initial density increases. This work was further verified by Abele and Gow (1976) in high-density snow at higher penetration rates. Table 2 summarises the variation in strain with density obtained by comparing depth of penetration with snow depth, for snow of different initial density, subjected to constant stress (from Abele and Gow, 1976).

**Table 2** – At a constant stress the amount of linear strain varies with initial density (derived from Abele, 1970).

<table>
<thead>
<tr>
<th>Density (kg m(^{-3}))</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.48</td>
</tr>
<tr>
<td>450</td>
<td>0.42</td>
</tr>
<tr>
<td>500</td>
<td>0.35</td>
</tr>
<tr>
<td>550</td>
<td>0.28</td>
</tr>
<tr>
<td>600</td>
<td>0.22</td>
</tr>
<tr>
<td>650</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Scapozza and Bartelt (2003) in triaxial tests on snow show that volumetric strain is similar in magnitude to linear strain for snow of initial density 270 kg m\(^{-3}\) at various confining pressures. If this relationship is assumed to apply to snow of higher initial density, then...
values for volumetric strain can be assumed similar to those values for linear axial strain presented in Table 2. This relationship is also assumed to hold across a range of applied stresses; this is consistent with data presented within Abele and Gow (1976). Therefore, the stress increase required for densification across a range of densities can be estimated from Mellor (1975) and stress multipliers for each density can be generated. These estimates are shown in Table 3.

**Table 3** – Stress multiplier derived from assumed initial and final density and pseudo-constant post-test wall thickness of ∼2.2 mm; see Figure 7.

<table>
<thead>
<tr>
<th>Initial Density (kg m^{-3})</th>
<th>Volumetric Strain</th>
<th>Assumed Final Density (kg m^{-3})</th>
<th>Approximate Pressure Multiplier (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.28</td>
<td>555</td>
<td>3.7</td>
</tr>
<tr>
<td>450</td>
<td>0.24</td>
<td>590</td>
<td>5.3</td>
</tr>
<tr>
<td>500</td>
<td>0.2</td>
<td>625</td>
<td>7.2</td>
</tr>
<tr>
<td>550</td>
<td>0.16</td>
<td>660</td>
<td>9.2</td>
</tr>
<tr>
<td>600</td>
<td>0.13</td>
<td>690</td>
<td>11.1</td>
</tr>
<tr>
<td>650</td>
<td>0.09</td>
<td>720</td>
<td>11.6</td>
</tr>
</tbody>
</table>

This multiplier is assumed valid for the range of densities shown in dry polar snow; snow temperature and grain size are not considered. This table shows that as initial density increases, volumetric strain decreases, change in density decreases and the pressure to produce volume change increases, as suggested by an increased multiplier. These trends are consistent with Kartashov (1965), Abele (1970) and Abele and Gow (1976), and may suggest how the pressure multiplying factor varies at different initial snow densities. Fitting the data in Table 3 allows $M$ to be estimated for any density using:

$$M = (0.0335\rho_{\text{initial}}) - 9.5828 \text{ for } 350 < \rho_{\text{initial}} < 650 \text{ kg m}^{-3}$$  \hspace{1cm} (3)$$

$M$ can be used to estimate the second term ($S_{\text{vert}}$) of equation 1 to derive tip resistance in snow of different initial density. This second term is purely a multiple of the first term $C$ and the estimated multiplier ($M$) obtained from equation 3 and is of the form $M \times C$.

The third term of equation 1, $F_{\text{vert}}$, due to the surface friction between compacted snow particles and the surface of the cone, is merely the frictional force on the cone face due to the normal force generated during compaction. A coefficient of friction for snow of $\mu \approx 0.1$ is indicative of values presented by both Bowden (1953) and Colbeck (1988), so an unresolved value for $F$ is obtained by multiplying the second term in equation 1 by 0.1.

McCallum (2012) compared resistance values averaged over depth with penetration rates varying from 0.16 mm s^{-1} to 55 mm s^{-1} and showed that tip resistance decreases with rate of penetration. Because the strength data within Mellor (1975) is obtained at rates much less than those typically used in CPT, resistance obtained via CPT may be $\sim 20\%$ less than the actual value. Therefore, strength values from Mellor (1975) should be reduced by 20% before incorporation into equation 1. This reduction will only affect the first term ($C_{\text{vert}}$).

Also, investigation into the effect of cone effective area on penetration resistance (McCallum, 2012) suggests that for a standard cone of diameter 36.7 mm in snow of observed mean grain size $\sim 0.7$ mm, the effective area of the cone will likely be greater than the actual cone cross-sectional area by perhaps $\sim 7\%$, thus resulting in potential misreading of actual resistance. Thus, in attempting to estimate CPT resistance values, calculated resistances should be increased by this amount to more accurately represent expected resistance.
Description of the terms within equation 1 plus consideration of modifying factors is now complete and a final form of an equation estimating tip resistance from snow shear strength can be derived.

In summary, the terms to incorporate are: \( C \) – the shear strength of the snow; \( S \) – compactive element, equal to \( M C \); \( F \) – friction on cone face, equal to \( (\mu S) \); reduction of \( C \) by 20% owing to rate, and increase of 7% owing to effective area. This results in the following equation:

\[
q_c = 1.07[0.8\left[(M+1)C_{vert} + \mu MC_{vert}\right]]
\]  

which assuming \( \mu \) is 0.1 and resolving \( S \) and \( F \) vertically by multiplying by 0.5 (cos 60°) and \( \sim 0.87 \) (cos 30°) respectively reduces to:

\[
q_c = 0.856(C(0.5 + 0.587M))
\]  

This equation incorporates all of the terms of the original conceptual model plus modifying factors; but, all strengths incorporated are shear strengths. The right-hand side of Equation 5 is multiplied by two to arrive at an estimate for snow resistance in compression (via CPT). The resulting final equation is:

\[
q_c = 1.7(C(0.5 + 0.587M))
\]  

This equation enables snow shear strength (herein assumed equivalent to cohesion) to be directly estimated from CPT tip resistance data.

**Validation**

If a typical value of cohesion for snow of initial density 450 kg m\(^{-3}\) of \( \sim 100 \) kPa is considered (from Mellor, 1975), then a multiplier (\( M \)) of 5.3 can be obtained from Table 3. This results in an estimated cone tip resistance of \( \sim 610 \) kPa. The average tip resistance between 1.0 and 1.2 m depth in Test 9, where density was \( \sim 450 \) kg m\(^{-3}\), is \( \sim 570 \) kPa. This comparison is favourable.

Applying this more generally: the average gravimetrically-determined snow density in a pit excavated to a depth of \( \sim 4.7 \) m adjacent to Test 9 was \( \sim 390 \) kg m\(^{-3}\). From Equation 3 a value for \( M \) of \( \sim 3.5 \) is obtained and applying equation 6 to the mean depth-averaged tip resistance value for all tests at that site (1.33 MPa) results in a mean strength estimate of 30 kPa. This lies within the range of strengths (20 – 90 kPa) suggested by Mellor (1975) for snow of density 390 kg m\(^{-3}\). Equation 6 may provide realistic estimates of tip resistance from estimated shear strength data (or vice versa).

Figure 8 is a comparison of compressive strengths derived from the CPT tip resistance trace with confined compression test data obtained from sixteen samples extracted at discrete irregular depths down to 2.9 m from a snow pit adjacent to the CPT. Compression testing was conducted using a 36 mm diameter flat plate connected to the CPT apparatus, with samples confined within a 100 mm diameter steel tube.

Mean strength values differ by only \( \sim 15\% \) and are not statistically different at the 95% confidence level (via unpaired t test). This comparison suggests that representative compressive strength values may be obtained using Equation 6. Apparent differences may be because of:

1) **Different data sampling:** Compressive testing was conducted on samples extracted from discrete depths, whereas the compressive strength from CPT is derived from averaging continuous CPT data over equivalent depths;

2) **Rate:** The tests were conducted at different rates, hence variation may be expected;

3) **Confinement:** Both tests were on semi-confined snow, although the compression tests were conducted within a rigid sleeve, hence differences in confinement may have contributed to variations;

4) **Flat plate versus cone:** CPT strength data was derived from a cone whereas the compressive testing used a flat plate;
this may cause some difference, although geometry effects are considered in deriving strength from CPT resistance, and

5) Natural variability: Snow displays large natural variability in strength hence variation between these compared values is not unexpected.

Shear strength testing at Halley was only conducted on surface layers, hence limited comparison between CPT-derived strength values and measured shear strength values is possible. Only a general assessment of average values can be made (Table 4).

In this table the average shear strength value for all the shear strength tests in the location of the Halley vehicle park is compared with shear strength derived from the average tip resistance (to 0.1 m depth) for the initial nine tests in the vehicle park using equations 3 and 5 for an average snow density across the shear tests of 550 kg m\(^{-3}\).

The estimated shear strength values via CPT lie within the range of historical data within (Mellor, 1975), ~1-200 kPa for snow of density ~ 550 kg m\(^{-3}\). They approach the order of shear strength measured via direct shear tests at Halley, however, difference is apparent, possibly because of differences in strain rate, size effects and the difficulties in obtaining accurate shear strength data in hard snow using the shear box. Whilst this limited comparison is not favourable, estimated shear strength values are consistent with published data.

**Table 4** – Comparison – average shear strengths and average tip resistance – Halley vehicle park.

<table>
<thead>
<tr>
<th>Average Shear Strength (kPa)</th>
<th>Average Tip Resistance (top 0.1m) (kPa)</th>
<th>Average Shear Strength from tip resistance (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1110</td>
<td>111</td>
</tr>
</tbody>
</table>
Estimating density from Cone Penetration Tests

Density alone is not an adequate descriptor for the mechanical behaviour or physical characteristics of a snow layer, but it is readily understood and historically utilised (McCallum, 2012). Variation of CPT data with density is therefore of interest. Resistance may vary within snow of the same density because the microstructure of the snow is different, but microstructural changes typically accompany changes in density, hence variation of both tip resistance and sleeve friction with density is expected.

Variation of both tip resistance and sleeve friction with density is shown in Figure 9, where tip resistance and sleeve friction are plotted with density.

Figure 9 shows good qualitative correlation between tip resistance and density. Although the resistance trace varies within each layer (owing to the distance required to reach steady-state resistance), variations in resistance agree well with density variations. Particularly hard and soft layers are evident, coinciding well with very dense and less dense layers, and both resistance and density are observed to generally increase with depth.

The increase of tip resistance with density is expected. It is consistent with the positive correlation between hardness derived from another penetrative instrument, the Rammsonde, and density (Gubler, 1975). Resistance variation in snow of the same density is expected because density does not necessarily imply the level of bonding within the snow, whereas measurements made by CPT (or other hardness measurements) will vary with such changes. Although a positive correlation between tip resistance and density is expected, quantifying this relationship is difficult because resistance does not vary in discrete layers (like density). Snow microstructural changes and cone size/shape affect the resistance data, but cross-correlation between density and layer-averaged resistance reveals a significant positive correlation of > 0.6. If the gradients of the density and resistance increase with depth are compared (0.0182 versus 0.1485), resistance is seen to vary by almost an order of magnitude more than density. This is consistent with the
understanding that snow not only increases in density with depth, but that increased sintering and strengthening of bonds within the snow also occurs, but not necessarily with a change in density.

The relationship between friction sleeve data and density is perhaps more complex. Sleeve friction may be positively correlated with density (McCallum, 2012) and with tip resistance, and tip resistance is positively correlated with density, thus a positive correlation between sleeve friction and density is probable. Numerous authors (Casassa et al., 1991; Colbeck, 1994) have noted the decrease in kinetic friction with increasing density, and Mellor (1964) and Erickson (1955) both note a decrease in friction with grain size. Grain size generally increases with depth during densification (although the increase to a depth of 5 m may only be of the order ~ 0.1 mm (Rick and Albert, 2004)), hence some decrease in friction with increased density is implied. This is contrary to observations made via CPT.

Figure 9 suggests that sleeve friction may change with density. Lag in the friction trace is evident, but this is not unexpected because of the physical location of the friction sleeve behind the cone tip. Between 2.5 m and 4.5 m sleeve friction is seen to qualitatively trend very well with density. Both friction and density increase with depth, albeit friction (similar to tip resistance) increases at a greater rate. The cross correlation between density and sleeve friction is ~ 0.6 (Pearson correlation significant at the 0.01 level (2-tailed)).

This observed increase in sleeve friction with density is assumed to be due to an increased normal force acting upon the friction sleeve caused by less efficient packing of fractured particles at the cone shoulder as the density of the snow undergoing penetration increases. Such a process would cause greater sleeve friction to be measured in higher density snow. This supposition is supported by data presented in Figure 10.

This shows that friction values in pre-drilled holes (where less mass will be packed)
are substantially lower than standard friction values, suggesting the influence that normal force may have on sleeve friction values. Examination of flat-plate data presented by Abele (1970) also shows that as density increases, penetration resistance also increases and penetration distance decreases. These observations support the supposition that an increase in density will result in increased friction, not because of grain size variations but because of the increase in normal force acting on the sleeve.

Sleeve friction has been shown to increase with snow density, and although this variation may be ‘damped’ (because of the decrease in density variability post-compaction), it is still expected that a qualitative variation of density can be obtained by observing the variation of friction measured via CPT with depth. Can a quantitative assessment of density be made from sleeve friction?

A linear line of best fit can be applied to an X-Y scatter plot of density versus average friction such that a relationship between the two variables can be established. However, the imprecision of the measurements, particularly density, do not allow a confident application of this method at this time. It is proposed that, in conjunction with a higher resolution density trace (such as that obtainable via neutron probe (Morris and Cooper, 2003)), a stronger correlation between sleeve friction via CPT and density could be established. This would mean that independent density measurements may not be necessary, and density estimates to enable calculation of the density-dependent strength multiplying parameter could be calculated, thus allowing estimation of a snow strength proxy directly from CPT. Ideally, testing would occur in homogeneous snow of known density over a period of time, allowing exploration of the relationships between density, sleeve friction (tip resistance also) and evolving snow microstructure.

Further testing is necessary, however, it appears probable that an estimate for relative snow density could be obtained directly from CPT sleeve-friction data.

### Estimating snow microstructure from Cone Penetration Tests

Changes in resistance measured by the cone may be the result of changes in density or changes in microstructure. This is because of the variation in stress needed to compact snow of varying initial density, and the increased stress needed to fracture more, or due to more-developed bonds between ice grains. Tip resistance is seen to vary with density (on a layer scale), and generally microstructure and density will go hand in hand, so that an increase in microstructure (i.e., increased number of bonds and/or thickness of bonding) will generally result in increased density. However, an increase in density (more mass per volume) does not necessarily mean an increase in microstructure (an increase in bonding).

In homogeneous snow it might be expected that sleeve friction would be correlated with tip resistance, and even in the heterogeneous data considered thus far, this appears the case. Therefore the ratio between these two values, the friction ratio \( R_f = f_s/q_c \times 100\% \) might be expected to be approximately constant.

As the level of bonding increases, this ratio should start to deviate. Tip resistance will increase (owing to the need to now fracture more bonds) whereas sleeve friction readings should remain similar, as the compacted snow forming the hole annulus from fractured material is indifferent to the amount of initial bonding. Friction ratio should therefore decrease as the amount of bonding increases. Can this variation in friction ratio suggest variation in snow microstructure?

Figure 11 shows the variation in tip resistance versus normalised sleeve friction...
This figure shows that for each sleeve friction value (y-axis) there is a range of tip resistance values (x-axis). Whilst some of this variation may be because of changes in density, any variation at the same density may be indicative of variations in microstructure, with higher tip resistance for the same sleeve friction suggesting a more-bonded layer.

This supposed phenomenon is difficult to illustrate, however, examination of snow pit data suggests that some layers were encountered with similar density but different microstructure (as determined by observation, grain size and hardness). Comparison between these layers may be expected to reveal similar sleeve friction values, but different tip resistance values, evidenced by a large difference in friction ratio. Table 5 compares this limited data.

This comparison seems to suggest that differences in friction ratio for layers of the same density may provide an indication of snow microstructure, however, in this case the variation in friction ratio is opposite to that expected. Lee and Huang (2010), in CPT tests on cemented sand, found that the increase in tip resistance (owing to cementation) increases linearly with cohesion, and that the increase in tip resistance between unbonded and bonded material can be up to 4 to 5 times. These findings and the rationale above suggest that a correlation between friction ratio and microstructure may be warranted. However, owing to the complicated nature of the field data, and the inability to extract precise data, further laboratory testing in

Table 5 – Friction Ratio variation between similar layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (cm)</th>
<th>Density (kg m\textsuperscript{-3})</th>
<th>Hardness</th>
<th>Grain size (mm)</th>
<th>Average Friction Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10 to 57</td>
<td>420</td>
<td>Finger</td>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>20</td>
<td>248 to 252</td>
<td>416</td>
<td>Finger/Pencil</td>
<td>1.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>
pre-defined snow is recommended in order to further investigate this relationship. Such findings further highlight that attempting to categorise snow by any one variable, such as density, hardness, or grain size, will always be problematic and that any snow ‘layer’ will often provide a unique combination of these parameters.

**Conclusion**

Modified CPT equipment was successfully used to obtain the first measurements of tip resistance and sleeve friction to depths of 10 m or more in polar snow. A physical model developed to estimate tip resistance from snow strength data was shown to reasonably predict (within \(\sim 15\%\)) tip resistance values. Further research is necessary; however, CPT may also provide estimates of snow density and snow microstructure, potentially enabling a continuous profile of three of snow’s primary physical characteristics – density, microstructure and strength – to all be estimated via CPT.

**Acknowledgements**

This research was only possible due to the generous assistance of Lankelma and Gardline Geosciences and the British Antarctic Survey, both in Cambridge, UK and Halley Research Station, Antarctica. This paper has been significantly improved due to the contribution of two anonymous reviewers; their time and effort on my behalf is both acknowledged and appreciated.

**References**


McCallum, A.B. 2013: Cone Penetration Testing (CPT) in Antarctic firn - an introduction to interpretation, Manuscript submitted for publication.


Manuscript accepted for publication 30 July 2013