CPT in polar snow - equipment and procedures

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ABSTRACT: Although manual cone penetration testing in snow has been practised since the 1930's, modern hydraulically-driven CPT equipment has not been used. Collaboration with the British Antarctic Survey will allow the first use of commercial CPT equipment in polar snow. This paper provides an introduction to polar snow, and outlines how existing CPT equipment has been adapted for Antarctic use. The interpretation techniques that will allow the determination of physical and mechanical properties of the snow pack are then briefly described. The knowledge gained through this research will contribute to improvements in design and construction of polar infrastructure.

1 INTRODUCTION

Investigation of snow pack physical properties has long been of interest to researchers, both as a means of assessing avalanche potential, and for estimating the load bearing capacity of snow pavements. Although Abele (1975) outlines three methods of strength assessment, surface load tests, sample testing and probing, only probing provides a time and cost effective insitu means of assessment.

The Swiss rammsonde, a portable impact penetrometer has been used since the 1930's to assess snow stratigraphy and the relative resistance of snow layers; it is still used today. Whilst rammsonde data can be interpreted to measure driving energy per unit penetration (cm-kgf/cm) (Mellor, 1975), and can be valuable in assessing the depth of weak layers, it is of limited value in calculating reliable empirical or physical relationships due to the rate-dependency of snow.

In 1985, Schaap and Fohn (1987) used a modified electric cone penetrometer with a cone diameter of 11.3mm that was manually pushed into the snow, to conduct preliminary investigations in alpine snow. Although the smaller cone allows high resolution of snow layering, the manual insertion method and restricted capacity limit the usefulness of a similar device in Polar snow.

Numerous other instruments have been developed for assessing snow strength and stratigraphy (Bradley, 1968; Dowd & Brown, 1986; Mackenzie & Payten, 2002; Schneebeli & Johnson, 1997) however they are all limited in depth and capacity, and are not suited for assessing dense polar snow packs where strength in uniaxial compression may approach 3 MPa (Mellor, 1975).

The use of existing geotechnical cone penetration test (CPT) equipment provides suitable robustness and capacity for conducting CPT in hard Polar snow packs.

2 THE NATURE OF POLAR SNOW

Polar snow is a sedimentary geomaterial consisting of ice and air; free water is rarely found within a polar snow pack. It is typically laid down seasonally, and undergoes metamorphism under overburden pressure and insitu temperature and vapour gradients. Mass is typically transported towards the surface, ice grains increase in size, and compaction and sintering result in densification with depth. Snow strength is correlated with snow density (Fig. 1), although variations in both snow microstructure (bonded or unbonded) and testing rate result in variation about this projection.

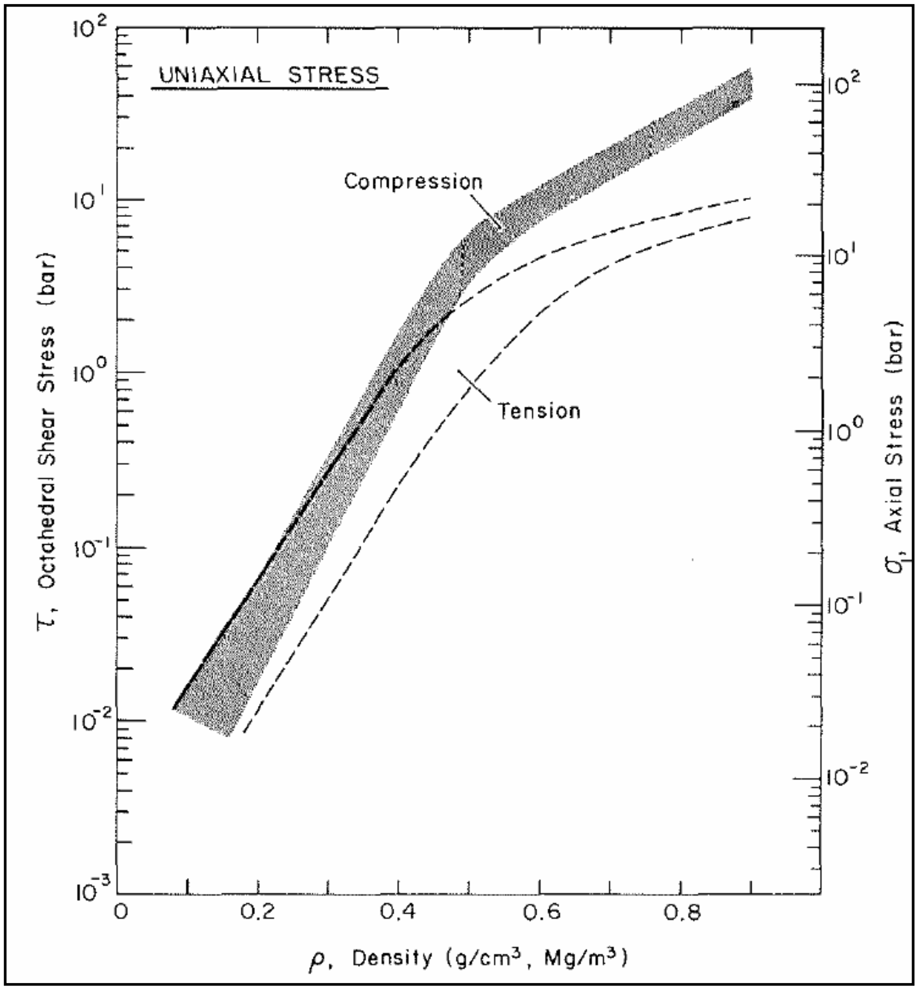

Figure 1. Snow strength vs density (from Mellor, 1975)

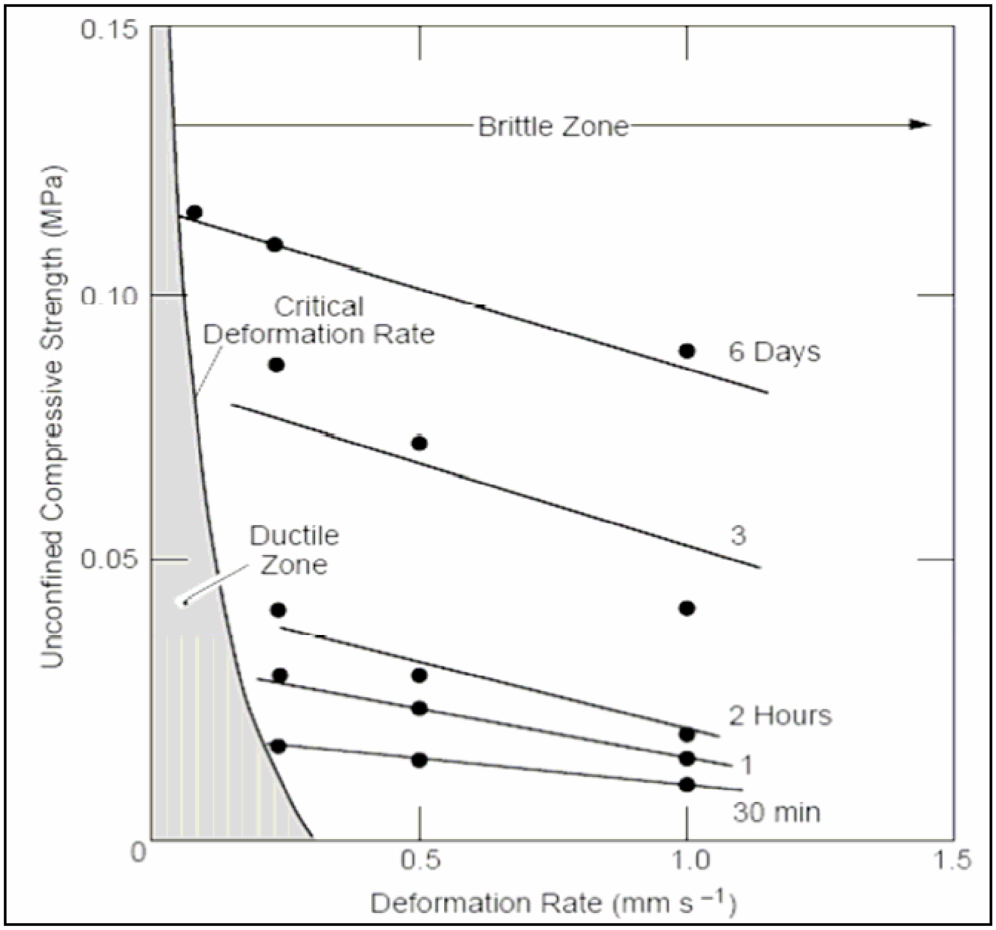

Figure 2. Snow strength vs deformation rate (from Shapiro et al., 1997)

Subjected to cone penetration at a penetration rate of 20mm/sec, polar snow is expected to behave in an elastic brittle manner, possibly similar to cemented soils. Substantial compaction is expected to occur up until the close-packed density of ~ 550 kg/m^3.

The primary constituent of snow, ice, is a rate-dependant material (Fig. 2). Accurate knowledge of the penetration rate enables an effective strain-rate to be estimated, so that comparisons with laboratory determined strength indices can be made.

3 FIELD TESTING

With the assistance of the British Antarctic Survey, access will be provided to the environs of Halley Base on the Brunt Ice Shelf Antarctica (Fig. 3). Construction of a new base consisting of modules weighing up to 60 tonne (Fig. 4) is currently underway, and assessment of snow stratigraphy and mechanical properties via CPT may prove valuable.

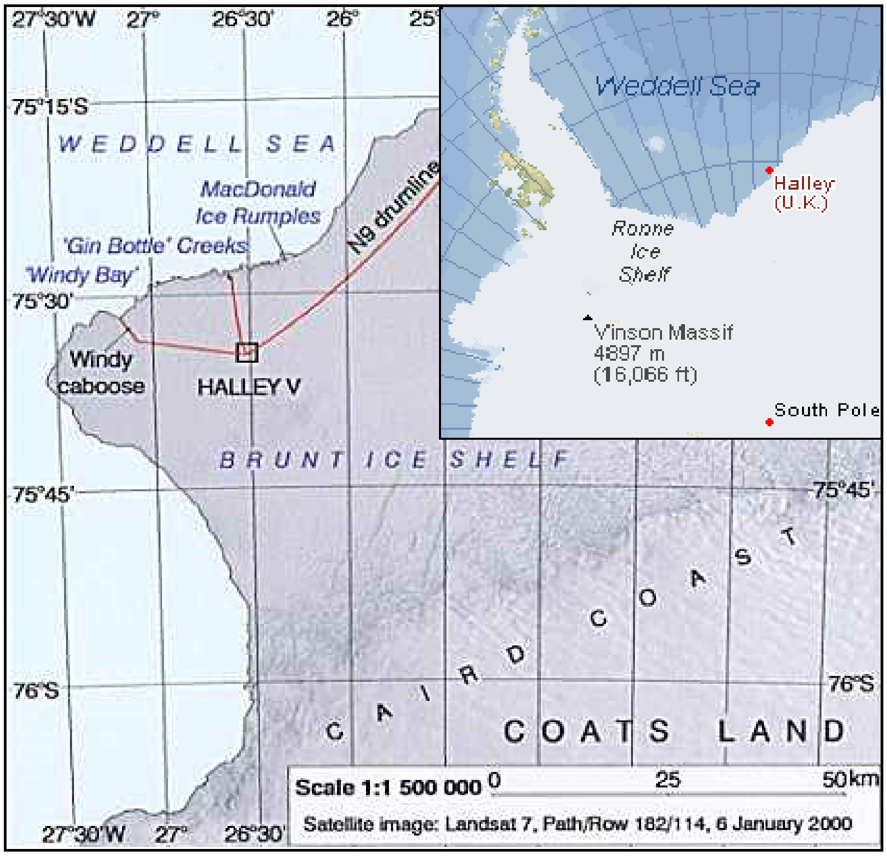

Figure 3. Test location (from http://www.smitha.demon.co.uk/zfids/index.htm)

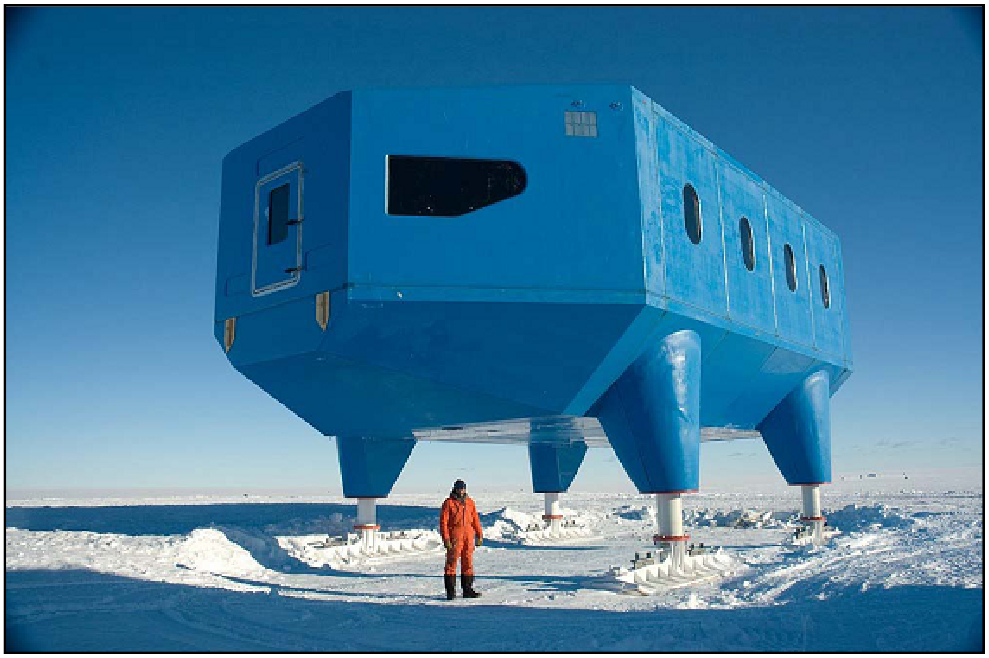

Figure 4. Halley VI Base module (courtesy British Antarctic Survey)

Testing will occur to a depth of 5-10m depending on snow conditions, across a variety of natural and compacted snow surfaces. Assessment of snow density, unconfined compressive strength and pressure bulb extent will also occur to assist in the interpretation of CPT results. GPR will be used to investigate spatial extent of distinct layers.

4 EQUIPMENT

A set of 10kN 'basement' rams with a stroke of 70cm was mounted within a fabricated steel box and connected via rigid framework to a proprietary steel A-frame, designed to attach to a standard agricultural tractor three-point hitch (Fig. 5). This hitch is standard upon the agricultural tractors to be utilised in Antarctica. The standard three-point hitch cannot counter an upward reaction force, hence an additional rigid link is required connecting the base of the A-frame with the upper tractor-link connection. Additional screw anchors can be attached to the box should additional reaction force be necessary. This arrangement should allow rapid testing over a large area using whichever vehicle is available.

Hydraulic drive is provided using down-rated flow of 10 L/min from the tractor, and electrical power is provided via an inverter mounted within the 'box', connected to the tractor's 12V electrical system. A. P. van den Berg 35.7mm 'scientific' compression cones will be used, along with standard "Gonsite!" software (http://www.apvdberg.nl/index.php?page=content.php&page_id=172&language_id=23.)

Figure 5. CPT equipment, Lankelma UK 11 (Courtesy Lankelma)

5 CONE CALIBRATION

Cone calibration was conducted in the Cold Rooms of the Scott Polar Research Institute (SPRI) to verify the zero-shift and linearity of the cones over the expected operational temperature range. Four cones similar to those that will be used were tested for linearity at room temperature, and dissipation tests (i.e. monitoring readings with time as the cone adjusts to constant room temperature) were conducted on two cones, measuring the variation in q_c, f_s, and u over the temperature range +23°C to –20°C. The variation in tip resistance at zero applied load is presented for two cones (Fig 6).

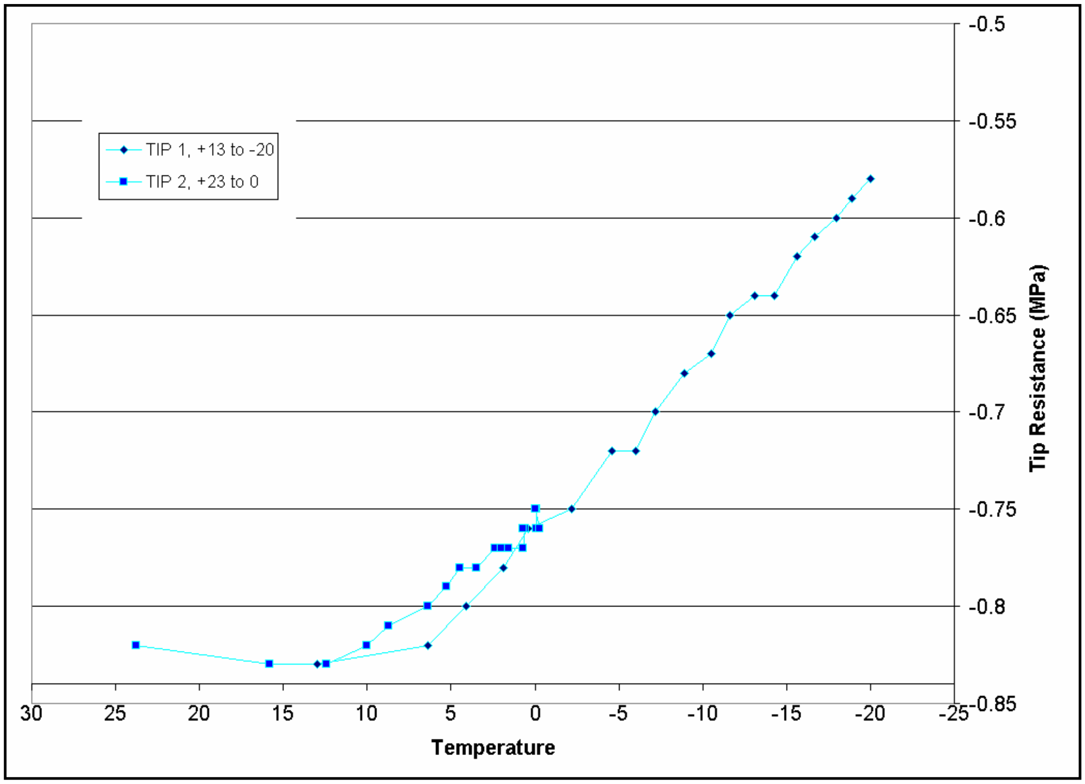

Figure 6. q_c zero-shift versus temperature

These preliminary results suggest that at temperatures greater than 8°C, temperature compensation is achieved by the cone temperature compensation system, but below this temperature, the zero-shift is inversely proportional to temperature. Consistent with the physics of thermal conductivity, it appears that the rate of temperature equilibration decreases as the thermal gradient decreases. The operational consequence of this preliminary testing is that below 8°C, cones should be allowed to equilibrate with environmental conditions for at least one hour before use, and that at sub-zero temperatures, limited zero-shift is expected in a test duration of approximately ten minutes.

Plots of cone millivolt output versus applied load were generated for two cones at temperatures of +20°C, 0°C, and –20°C. In each of these tests, although limited data were available, the gradient in each test was essentially constant (R = 0.88), with the axial intercept varying with temperature as defined by the dissipation tests.

This preliminary calibration testing concluded that cone output (mV) appears to vary linearly with applied load (N) throughout the operational temperature range, with only the axial intercept varying with temperature.

6 ADDITIONAL CONSIDERATIONS

Aside from cone calibration, additional modifications to the CPT need to be incorporated to allow accurate testing in the Polar environs. Snow has been observed to sinter or to re-bond within sub-second timescales (Szabo & Schneebeli, 2007) hence sintering of disaggregated grains ahead of the cone, as well as refreezing of melt water generated during penetration may occur. Such mechanisms will likely result in anomalous ‘spikes’ within the data, and will need to be considered. Tests will be conducted at staggered depths to ensure a complete data record.

Laboratory testing of cones in snow suggests that a compacted zone of fractured material may move ahead of the cone, effectively displacing the bearing surface ahead of the cone. Such mechanisms need to be verified to allow for accurate interpretation, and additional laboratory testing will occur to further investigate this phenomenon.

The use of a standard 35.7mm cone means that thinner strata, often evident within snow packs may not be detected during testing, however comparison with manual density and stratigraphy data, should allow deflections in the signal due to convolution of such layers to be identified.

7 INTERPRETATION

Dense polar snow is expected to yield in a brittle manner before substantial compaction and possibly strain-hardening may occur. Although snow is typically modeled using a Mohr-Coulomb or Drucker-Praeger model (Shoop & Alger, 1988; Johnson, 2003), dense polar snow is expected to behave in a manner similar to soft, porous rock. Behaviour may be similar to that described by Houlsby et al. (1988) during penetration of model piles into layered carbonate soils. An elastic brittle stress-strain model will be assumed whereby frictional strength of the fractured granular material will not be realised until after cohesion is lost upon initial brittle fracture of the material.

Interpretation of the CPT tip-resistance signal will be attempted using numerous methods:

1. Direct comparison with density measurements, using qualitative microstructure assessment,

2. Attempted signal deconvolution using estimated pressure envelopes ahead of the penetrating cone, and comparison with the density record,

3. Closed form analysis and FEA of the cavity expansion solution in a infinite porous elastic-brittle material, and

4. Equating Work in penetration with estimated summative bond strength.

Further discussion on the analysis of results will be presented in subsequent forums.

8 CONCLUSION

Assessment of snow strength for the design of polar infrastructure may be efficiently assessed through the use of a hydraulically driven, rate-constant, portable cone penetrometer. The ability to adequately interpret such data may prove of substantial benefit in the design and construction of infrastructure in the cold regions of the world.

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