Assessing mass balance with the cone penetration test

This letter briefly outlines why a friction-sleeve-equipped cone penetrometer may be a useful tool for assessing surface mass balance of polar ice masses.

Mass balance is defined as ‘the change in the mass of a glacier, or part of the glacier, over a stated span of time’ (Cogley and others, 2011). Historically, glaciological mass balance was assessed using repeat surface measurements of a stake network where temporal changes in ablation or accumulation were recorded (Ostrem and Brugman, 1991). Today, this role is increasingly performed over large spatial scales using geodetic methods. Satellites such as ICESat, CryoSat II and GRACE use various methods to calculate ice mass volumetric change over time (Shepherd and others, 2012). However, empirical surface mass-balance assessment is still necessary to ‘ground-truth’ and constrain models that utilise satellite-derived geodetic mass-balance data.

Methods that can be used to assess mass balance include: ablation and accumulation measurements using stakes; static ultrasonic depth sensors; avalanche probes (for shallow assessment); snow pits; the ‘coffee-can’ method (Hamilton and others, 1998); borehole techniques such as the neutron probe or borehole optical stratigraphy (Hawley and Morris, 2006); and by assessing extracted cores with instruments such as the MABLE (mostly automated borehole logging experiment) (Breton and Hamilton, 2012). Today, this role is increasingly performed over large spatial scales using geodetic methods. Satellites such as ICESat, CryoSat II and GRACE use various methods to calculate ice mass volumetric change over time (Shepherd and others, 2012). However, empirical surface mass-balance assessment is still necessary to ‘ground-truth’ and constrain models that utilise satellite-derived geodetic mass-balance data.

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McCallum (2014b) described the first use of a friction-sleeve-equipped hydraulically driven cone penetrometer, the Cone Penetration Test (CPT) in Antarctica. It was used to penetrate snow and ice layers with strength of up to 40 MPa, to depths of 10 m. Further work described methods by which snow density, relative microstructure and strength can all be estimated using data obtained from the friction-sleeve-equipped penetrometer (McCallum, 2014a; McCallum, 2014c).

This letter briefly outlines why repeated use of a friction-sleeve-equipped cone penetrometer may be useful for assessing surface mass balance of glaciers and ice sheets.

CONCLUSION

Mass-balance assessment of glaciers and ice sheets is crucial to constrain ice mass models. However, existing techniques do not enable efficient point assessment to depths >1 m in hard polar snow. The CPT has the potential to offer a simple and robust method that can be easily repeated over time to enable mass balance to be determined.

It is likely that a quantitative relationship exists between CPT sleeve-friction data and snow density that can be applied to depths of 5–10 m in polar snow. However, only one field campaign has been conducted with this friction-sleeve-equipped penetrometer (McCallum, 2014b) and additional controlled field or laboratory testing is necessary to refine this relationship.

CPT data presented herein were collected using heavy equipment (Fig. 1). However, a lightweight modular CPT system that can be transported by Twin Otter or equivalent aircraft and towed by a snowmobile is currently being constructed. This should enable the rapid acquisition of surface
Fig. 1. Tractor-mounted CPT equipment used at Halley V Research Station, Antarctica, 2009/10. Insets show: a rigid steel link (∼100 mm outside diameter) that can be engaged to enable additional reaction force from the ∼20 tonne tractor, and hydraulic rams and data collection equipment (from McCallum (2014b)).

Fig. 2. Tip resistance (MPa) for six individual tests to a depth of 5 m is shown along with an average value. Negative spikes apparent every 0.5 m occur when penetration was stopped to change rods; these spikes are generally removed in post-acquisition data-processing. The cone responds to harder and softer layers; layer interfaces can be identified to a resolution of ∼25 mm. Data were collected on the Brunt Ice Shelf in the vicinity of Halley V Research Station in 2010.
mass-balance data from remote polar and accessible alpine ice masses. Moreover, CPT can be conducted with additional commercially-proven in-line sensors such as a resistivity module or a video module to enable comprehensive assessment of snowpack properties during a single test.

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REFERENCES


Fig. 3. Comparison of sleeve friction, averaged over friction-sleeve length and normalised for comparison purposes, with gravimetrically-determined snow density. In this figure, additional stress due to overburden has been subtracted from friction-sleeve data. Data were collected on the Brunt Ice Shelf in the vicinity of Halley V Research Station in 2010.