IN SITU TESTING OF RIVER-ICE STRENGTH USING A HYDRAULIC BOREHOLE JACK[1]

M.N. Demuth and T.D. Prowse

National Hydrology Research Institute
Environment Canada
Saskatoon, Saskatchewan
S7N 3H5

ABSTRACT

The borehole jack is a field-portable hydraulic indentation device which enables the *in situ* testing of the confined-compressive strength of ice. The device has been used extensively in the testing of first- and multi-year sea ice. Recently the borehole jack was also used to measure the relative changes in strength of river ice during the period of pre-breakup decay. A test program was conducted on the Liard River, N.W.T., Canada in April and May of 1987. The principles of ice indentation testing are briefly reviewed and details of jack operation are given. Recommendations are made regarding the interpretation of borehole jack data and possible improvements to jack design and operation.

INTRODUCTION

The borehole jack has been utilized primarily as a field-portable means for determining *in situ* mechanical properties of first- and multi-year sea ice in the offshore regions of the Arctic coast. Here, exploration for oil and gas from ice island platforms and man-made structures necessitates an understanding of ice strength and load bearing capacity. Similarly, for river-ice applications, such as the evaluation of over-ice conveyance and breakup prediction, knowledge of the mechanical properties of river ice is required to understand ice decay mechanisms and ice fracture/failure processes.

INSTRUMENT DESCRIPTION

Originally developed by FENCO (Kivisild, 1975), the borehole jack consists of a hydraulic cylinder (Fig. 1) which, when pressurized by a suitable pump, pushes indentor platens into the walls of a borehole cored in the ice sheet. For this study, the system used an electro-hydraulic pump capable of providing up to 69 MPa system pressure. Pump volumetric output is non-linear, varying from 655 mL/min to 197 mL/min at 0 and 69 MPa system pressure respectively (Geotechnical Resources Ltd.). Hydraulic fluid is routed to the jack via flexible hydraulic hoses that have a working pressure of 41 MPa and a burst pressure in excess of 69 MPa. Control of jack indentation/retraction is achieved with a directional control valve. Pump volumetric output is not controllable in this system and varies in an open-loop manner according to the resistance encountered during indentation.

---

[1] NHRI Contribution No.88051

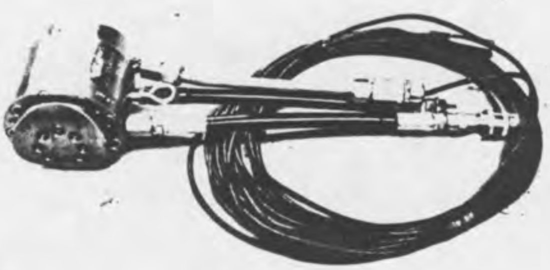

Fig. 1. Borehole jack test equipment.

Fig. 2. Jack inserted in test hole.

A typical test initially involves the vertical coring of a 150 mm diameter hole in the ice sheet without penetrating the entire thickness. The jack is then lowered to an appropriate test depth and pressure is applied to extend the platens into the walls of the borehole (Fig. 2). Hydraulic system pressure is measured by a pressure transducer and, after signal conditioning, the output is recorded on a strip-chart recorder. Applied platen pressure (stress, σ_1, MPa) is determined from system pressure by an area ratio of piston/platen = 0.63. Platen displacement (δ, mm) is measured by a linear variable resistor mounted within the jack body and the output is recorded simultaneously with system pressure.

INDENTATION THEORY AND ANALYSIS

The borehole jack performs, what can be classified as, a type II indentation in which the ratio of platen diameter to ice-sheet thickness is considerably less than 1.0 (Sanderson, 1986). The resulting stress field is triaxial as the platen displaces through what is essentially a semi-infinite solid. Contact with the borehole wall results in immediate localized crushing failure of the ice near the platen. This crushed bulb grows radially about the zone of contact as increased applied pressure induces further indentation. This continues until the ice extrudes around the platen and the test achieves a peak-yield condition. Often, particularly in warmer ice (i.e. near 0°C), the applied pressure-displacement history never attains a peak yield condition and the bulb of crushed ice continues to grow as applied pressure increases and asymptotically approaches an ultimate value. In extremely deteriorated ice, the platen may simply re-orient the ice-water matrix and not effectively load the ice sheet *per se*.

The yielded ice volume surrounding the platen-ice interface may be comprised of several distinct morphological zones produced by various combinations of compressive, shear and tensile forces (Fig. 3). The extent to which these zones are present depends on loading rate, ice temperature and the extent of thermal/structural decay. Because of the indeterminate nature of the strain distribution through these zones, borehole jack results can only be considered to provide an index of strength. In a conventional uniaxial test, where the yield morphology is less complex and the specimen remains accessible, the specimen strain can be measured directly. For the borehole jack test, however, strain must be indirectly defined at the platen-ice interface as the radial strain (ϵ_r). This may be derived from the platen displacement δ using $\epsilon_r = \delta/r_o$.

To properly evaluate the strength of a material, the loading history should be examined. The attainment of maximum strain rate in the material (for the jack test, $\dot{\epsilon}_{rm}$) indicates a level of damage such that the ice can offer no additional resistance as deformation increases. The validity of this for jack tests of decayed 0°C isothermal ice remains in question and is dicussed below.

For this study, the applied platen pressure and displacement data from each test enabled the construction of a "stress-strain" diagram from which peak-yield and ultimate strength

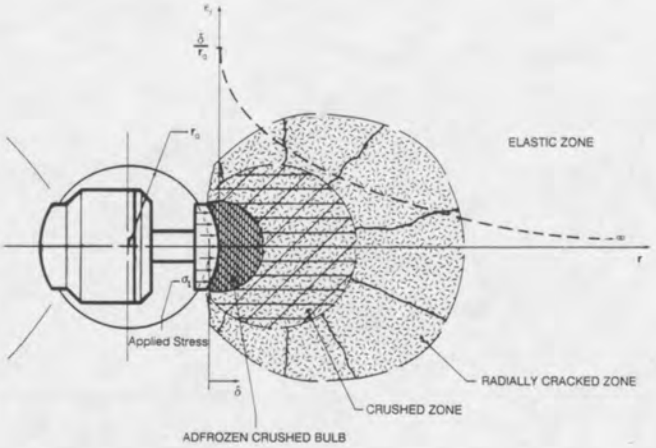

Fig. 3. Platen indenture geometry showing the possible yield morphology produced by the jack test (adapted from Masterson, 1983).

values were derived. The loading history was also examined to evaluate the attainment of $\dot{\epsilon}_{rm}$ as an indicator of "peak-yield failure" (Sinha, 1986).

STUDY SITE

Field tests were conducted on the Liard River; a typical large northern river where mature ice covers usually equal or exceed 1.0 m in thickness. The jack was used during the pre-breakup period which allowed testing in a variety of thermal and structural ice regimes. Details regarding the study site, jack test methodology and results of concomitant energy balance experiments can be found in Prowse *et al.* (1988a).

DISCUSSION

Figure 4 illustrates the loading history for a typical test conducted in a 0°C isothermal ice sheet which has not deteriorated structurally by internal radiative melt. It is characterised by a peak-type of yield failure, a coincidence of peak-yield (σ_{1p}) with the onset of $\dot{\epsilon}_{rm}$, and a relatively high post-peak strength (commonly observed for a variety of materials when loaded to failure in confined compression). None of these tests exhibited post-peak increases in resistance. In contrast, for an ice sheet which has undergone appreciable structural decay (Fig. 5), resistance gradually rises and only asymptotically attains an ultimate value, σ_{1u}. Note that $\dot{\epsilon}_{rm}$ (at σ_{1m}) occurs prior to the attainment of ultimate resistance. This effect may, in part, be due to the changing yield morphology about the platen as the ice progressively decays. See Prowse *et al.* (1988b) for detailed results of the strength analysis and the ice sheet decay morphology.

The occurrence of peak-yield versus asymptotic-ultimate behaviour is dependent on the thermal and structural characteristics of the ice and, more importantly, on the rate of load application. The stress- and strain-rate sensitivity of ice has been well documented (Gold, 1977) and considerable laboratory effort has been devoted to this aspect of ice strength (Sinha, 1982). To minimize the effects of rate sensitivity, closed-loop systems which enable constant stress-rate and strain-rate tests have been employed in laboratories. Operation of a closed-loop system requires the measurement of a representative material stress or strain for feedback purposes.

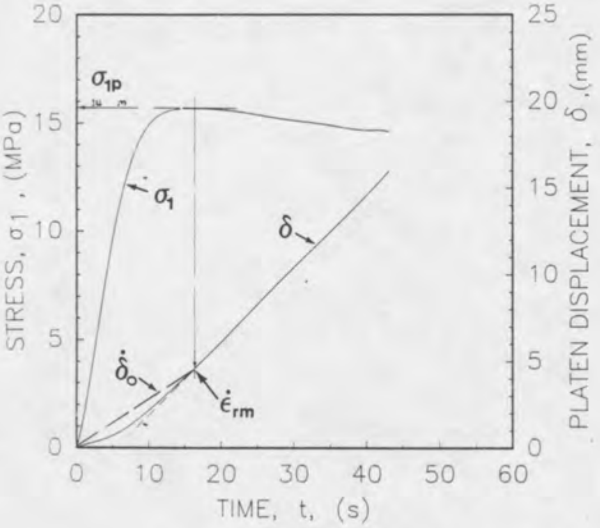

Fig. 4. Typical loading history for a structurally integral white-ice cover.

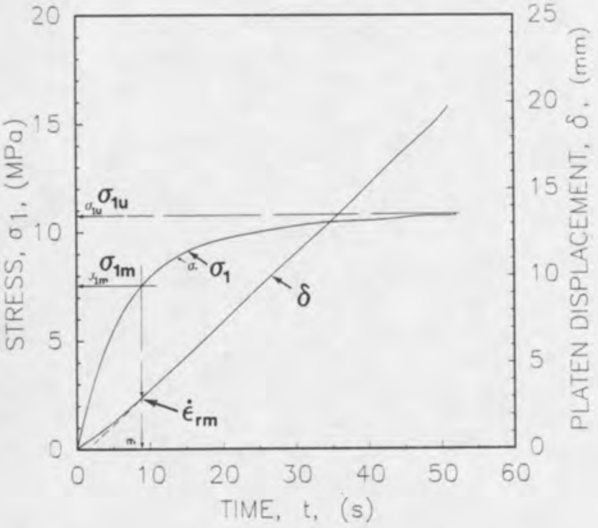

Fig. 5. Typical loading history for a decaying ice cover.

Although material strain cannot be measured in a jack test, the utility of the jack can be enhanced by the addition of a flow servo-control to allow constant displacement rate tests and a pressure servo-control for constant stress rate tests. Such modifications could simplify the interpretation of the jack test results by eliminating the rate dependent characteristics. The flow and pressure servo-controls required for testing in the pre-breakup river-ice environment are readily available albeit costly. Alternatively, the addition of a simple and inexpensive proportional flow control would allow adjustment of the nominal displacement rate, $\dot{\delta}_o$ (Sinha, pers. com., 1987). In this manner, given a variable thermal and structural ice regime, an operator can achieve some control over the effect of rate sensitivity on ice strength.

Control of $\dot{\delta}_o$ could also permit testing in relatively thin ice sheets. Adequate elastic confinement (thickness) about the platen-ice interface is requisite for a valid test. For example, Figure 6 illustrates the results of lack of confinement in thin (~ 0.6 m) 0°C isothermal ice for a test conducted at $\dot{\delta}_o = 2$ mm/s. Performing the test at a reduced $\dot{\delta}_o$ would have produced a smaller affected volume and ensured elastic confinement by undamaged ice. Notably, the failure surface illustrated in Fig. 6 shows evidence of the yield morphology described earlier.

Fig. 6. Shear failure surface produced by subsurface triaxial loading at indenture rates promoting brittle failure.

Platen design is an additional factor determining the behaviour of ice during indentation. Observations indicate platen surfaces should be smooth and devoid of stress raisers to minimize the possibility of generating premature failure. More work is also neccesary to investigate the effects of scale vis-à-vis platen size and aspect ratio. This has implications for testing ice sheets which exhibit large diameter, columnar-grained ice.

CONCLUSION

The operation of the borehole jack and the loading response of typical pre-breakup river-ice sheets under triaxial indenture is described. The rated sensitivity of the ice and the unknowns associated with the yield morphology that exist during indenture of structurally decayed ice, may account for the loading response observed. Improvements to the jack have been identified and account for the rate-sensitive nature of mechanical ice strength testing. These include the incorporation of flow- and pressure- servo-controls to enable constant displacement- and stress-rate tests. The ability to control loading rate extends to the utilization of the jack for the testing of thin ice sheets, where the yielding volume may, depending on load application rate, be inadequately confined causing premature failure. Additional testing is required to investigate the effects of platen geometry when working with the heterogeneous vertical morphology of typical river-ice sheets.

ACKNOWLEDGEMENTS

The authors thank Mr C. Onclin and Mr M. Hey (National Hydrology Research Institute) and Mr P. Wood and employees (Water Survey of Canada) for their valuable assistance in the field. Comments and suggestions by Dr N. Sinha (National Research Council of Canada) and Dr D. Masterson (Geotechnical Resources Ltd. from whom the FENCO borehole jack system was leased) are appreciated.

REFERENCES

Geotechnical Resources Ltd., 1982: Operations guide for the borehole jack test. Geotechnical Resources Ltd. Internal publication.

Gold, L.W., 1977: Engineering properties of fresh-water ice. Journal of Glaciology, Vol. 19, No. 81, p. 197-212

Kivisild, H.R., 1975: Ice mechanics. Proceedings of the 3rd International Conference on Port and Ocean Engineering under Arctic Conditions, University of Alaska, Fairbanks, Alaska, Vol. 1, p. 287-313

Masterson, D.M., 1983: Interpretation of *in-situ* borehole ice strength measurement tests. Symposium on the Mechanics of Ice, Rocks and Soils, A.S.M.E. Applied Mechanics, Bioengineering and Fluids Engineering Conference, Houston, Texas, U.S.A.

Prowse, T.D., Demuth, M.N., Onclin, C.R., 1988a: Strength and energy balance of decaying river ice. In - Applied Hydrology in the Development of Northern Basins, Proceedings, 7th Northern Research Basins Sumposium, 25 May - 1 June 1988, Ilulissat, Greenland, Danish Society for Arctic Technology, Copenhagen, Denmark, 29 March, 293-301

Prowse, T.D., Demuth, M.N., Onclin, C.R., 1988b: Using the borehole jack to determine changes in river-ice strength. Proceedings of the 5th Workshop on the Hydraulics of River Ice/Ice Jams, June 21-24, 1988, Winnipeg, Manitoba, (in press).

Sanderson, T.J.O., 1986: A pressure-area curve for ice. Proceedings of the IAHR Ice Symposium, August 18-22, 1986, Iowa City, Iowa, Vol.2, p. 361-384

Sinha, N.K., 1982: Constant strain- and stress-rate compressive strength of columnar-grained ice. Journal of Material Science, Vol. 17, p. 785-802

Sinha, N.K., 1986: The borehole jack. Is it a useful Arctic tool? Journal of Offshore Mechanics and Arctic Engineering, Vol. 109, No. 4, p. 391-397