The Borehole Jack Indentor Test
Recent Advances at NHRI

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INTRODUCTION

In the 1988 proceedings of the Eastern Snow Conference, Demuth and Prowse (1988) described the application of the borehole jack indentor in testing the strength of river ice. Subsequent work (Prowse and Demuth 1992, Demuth and Prowse 1992), has focused on three major research areas: i) determining the role of ice strength in controlling the resistance of the ice cover to forces associated with break-up, ii) describing the basic processes leading to the deterioration of freshwater ice, and iii) interpreting the behaviour of deteriorating fresh-water ice when under load by the jack.

Originally developed and applied by a variety of researchers in the fields of ice mechanics, bearing capacity and ice-structure interaction (e.g., Kivisild 1992, Masterson and Graham 1992, Sinha 1987), most work with the jack has centred around the testing of intact sea- and freshwater ice. Unfortunately, while attempting to quantify the results of testing in the deteriorating ice covers found on rivers prior to the onset of break-up, the authors of this paper experienced difficulty in using theories that describe the response of the jack in intact ice. This resulted because of the lack of information about the basic mechanical properties of deteriorating ice and, the behaviour of such ice under indentation did not replicate that of intact ice. It was clear that alternative methodologies and hardware systems required development.

This paper reviews: i) the basic mechanical behaviour of ice; in particular, contrasting that of intact polycrystalline ice to deteriorating ice, ii) how such behaviour influences the interpretation of the borehole jack indentor test, and iii) recent methodological and hardware advances made at the National Hydrology Research Institute (NHRI) and how these advances improved the utility of the jack test in pre-break-up river ice conditions and for *in-situ* ice testing in general.

MECHANICAL BEHAVIOUR OF POLYCRYSTALLINE ICE

The following sections outline the factors that control the load-deformation characteristics of ice in general and contrast the volumetric behaviour of intact polycrystalline ice with that for deteriorating ice.

General Characteristics

Ice exists, for most practical purposes, at a high temperature relative to its melting point and thus is expected to be ductile. Brittle behaviour is often observed, however, because of several factors controlling ice deformation under particular loading conditions. These include temperature, rate of deformation, stress concentration, grain morphology and the existence of inter-granular and interstitial voids/impurities. In general, under constant volume deformation, ice can be characterized as a viscoelastic strain-softening solid in which changes in grain shape are permitted by slippage at the basal plane. Constraints imposed by neighbouring grains can cause internal stress concentrations and further deformation occurs through grain boundary migration and recrystallization. If the material strain rate is high enough, however, crack formation can occur. Subsequent deformation no longer occurs at constant volume and the material enters a state of dilation (e.g., see Sinha 1991).

Deteriorating Ice

In contrast to intact polycrystalline ice, deteriorating ice contains networks of water-filled voids (e.g., Prowse *et al.* 1990). Observations of such ice under relatively low strain rates (e.g. creep conditions which preclude extensive cracking) suggest that compaction from void collapse may dominate the mechanical behaviour. It may also be reasonable to assume that, at higher strain rates, cracking activity and dilation must first be preceded by compaction (Figure 1).

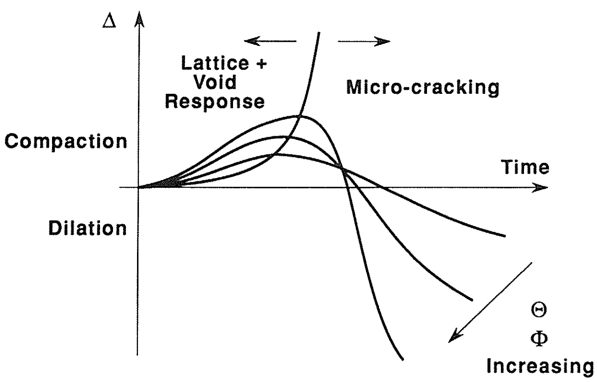


Figure 1 Conceptual model of volumetric strain (Δ) in a porous solid under compression. Θ and φ are temperature and porosity respectively.

Whether the voids act as stress concentrators, thereby promoting fracturing, or as stress relief sites which may arrest the progression of cracks, is unknown however. Furthermore, it is unknown to what extent such void space is interconnected. Increases in void pressure for a porous solid exhibiting limited connectivity may actually raise stresses surrounding the void and promote crack initiation and growth.

In general, further study is required to characterize the complex time and path dependent deformation characteristics of such ice under load. If such work is based on conventional laboratory-based approaches, it will be severely hampered by difficult sample recovery, preparation and deformation measurement. *In-situ* methodologies are one method to remedy this problem. Many, however, are complex, time consuming (e.g., bending tests) and simply not suitable. The portability and simplicity of borehole-based methodologies provide a safe and practical alternative to conventional testing. Furthermore, borehole-based techniques appear to offer the ability to sample quickly enough to obtain a valid statistical representation of ice properties. This is particularly important in river ice break-up where diurnal and temporal changes can be quite dramatic. Of these techniques, which include using the *pressuremeter* (e.g., Michel and Hodgson 1992) and other penetrometer devices (e.g., Ladanyi 1992), the borehole jack indentor represents the most adaptable device because of its similarity in methodological development to conventional uniaxial methods. The borehole jack indentor test and its interpretation are reviewed next.

BOREHOLE JACK INDENTOR

Basic Principles and Operation

The borehole jack indentor (Figure 2) performs a three-dimensional indentation, using curved, circular platens, into the wall of a borehole cored into the ice cover (e.g., Masterson and Graham 1992, Sinha 1987, Demuth and Prowse 1988). The platen pressure (P) and displacement (δ) history of the test are recorded. The P-δ characteristic obtained by open-loop jack platen indentation is similar to the *stress-strain* (σ-ϵ) characteristic of an open-loop uniaxial material strength test for ice. In general, both are characterized by a convex-up load-deformation curve leading to a yield state where the material cannot accept any significant increases in load and begins to strain to a post-yield state. The load-deformation characteristics of the post-yield state depend on the rate and mode of testing (e.g., confined, unconfined).

Interpretation of Results

Interpretation of the borehole jack indentor test is made difficult by: i) changing boundary conditions (e.g., evolving failure zone and degree of confinement) and device stiffness (e.g., mechanical seal resistance) during testing, ii) an indeterminant stress/strain field, and iii) changes in the ice induced by jack-platen/ice interaction. Indeed, similar factors influence other, more conventional test methods and thus, some degree of interpretation is generally necessary (e.g., the influence of scale, load arrangement and other test conditions).

In attempting to overcome these problems,

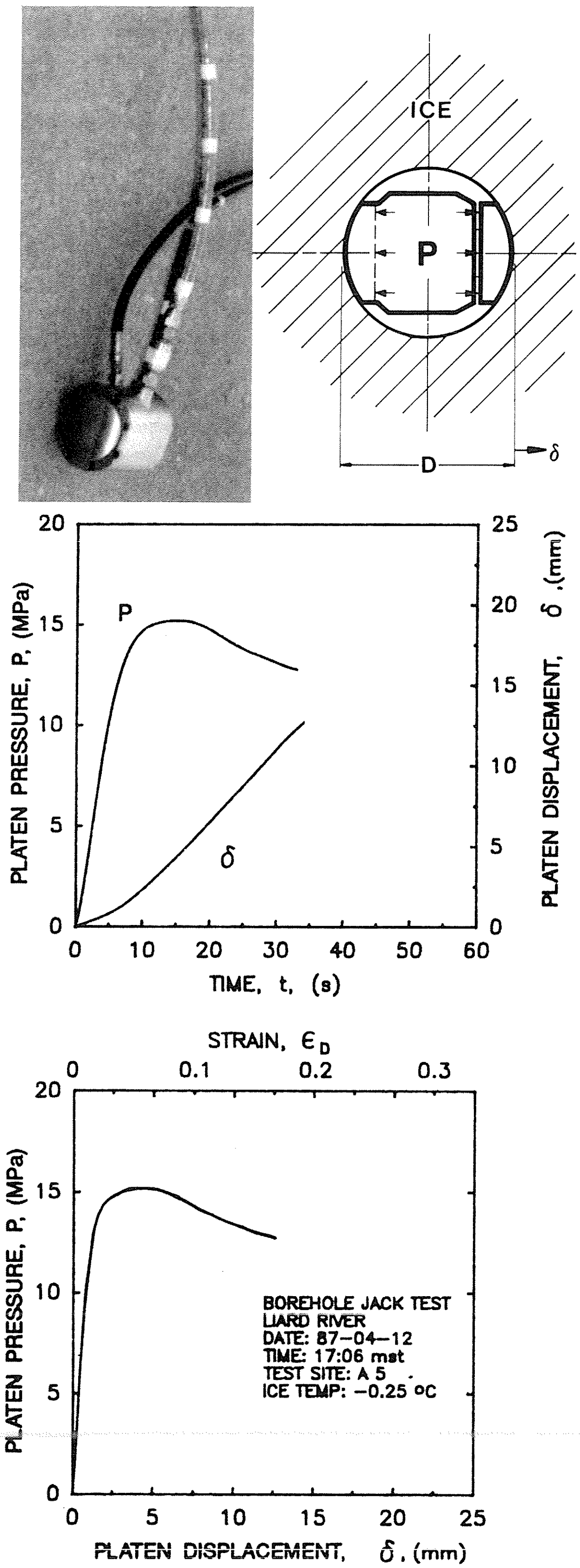


Figure 2 The borehole jack indentor, its deployment in an ice cover and a typical open-loop load-deformation response.

cavity expansion models have proven to replicate satisfactorily the basic P-δ characteristics of intact ice under jack indentation. Such models assume the formation of an incompressible, spherical crushed-bulb at the beginning of indentation. Subsequent indenture of this bulb creates increasing stress in the surrounding ice, eventually leading to a yield state. By geometric and constitutive considerations the compressive strength and strain modulus of the ice are predicted using a parametric approach (e.g., Masterson 1992). In general, however, the formation mechanism, geometry and mechanical properties of the bulb cannot be confirmed, especially in vertically anisotropic ice. Moreover, observations in deteriorating ice suggest that: i) significant indentation resulting in localized compaction must first take place (often observed in the initial P-δ characteristic as a *concave*-up trend), and ii) a bulb may form in ice having a relatively low porosity, however, a bulb does not generally form in highly deteriorated ice (e.g., $\approx$10% porosity) (Demuth and Prowse 1992).

The above uncertainties and complications have led others to relate specific jack results to other parameters. For example, Prowse and Demuth (1992a) obtained relative changes in the *jack strength* of deteriorating river ice covers concomitant with detailed energy balance measurements. This resulted in a unique temporal record of changing cover *resistance* prior to break-up. The jack has also been used to study the areal variability of pre-break-up ice covers (e.g., Prowse and Demuth 1992b). Sinha (1987) has shown that the jack is capable of measuring the rate sensitivity of ice strength and furthermore has shown that jack strengths correlate well with the results of unconfined- and confined uniaxial compression performed on the same ice.

The continued observation of ice behaviour in nature and the development and execution of standardized tests at a variety of scales, have led to marked improvements in our knowledge of the mechanical properties of ice. The advancement of the conventional uniaxial test with respect to machine stiffness and sample strain/stress path control has fostered similar hardware and methodological developments for the *in-situ* borehole jack indentor test (e.g., Masterson and Graham 1992, Sinha 1987, 1990). Development work at the National Hydrology Research Institute relates specifically to applying the jack in studies of the hydrology and environmental effects of river ice break-up. This work has concentrated on extending the capabilities of the jack in *thin* ice and improving the control system used to impart and measure the ice load-deformation characteristic, the latter being important to investigating *in-situ*, the volumetric behaviour of ice under load.

RECENT ADVANCES IN TEST METHODOLOGY AND HARDWARE AT NHRI

Methodology

Measuring strength and strain modulus

To date *jack strength* has been defined in a number of ways: i) the ultimate platen pressure attained at *full* indentation, (i.e., at maximum actuator travel) and, ii) the platen pressure when the loading history indicates a *yield condition* (for an open-loop test, this condition is revealed where the platen displacement rate becomes a constant maximum). Such measures, although indices, have been useful as previously described. To lend additional physical basis to test interpretation in deteriorating ice, the authors have applied a simplified plastic limit analysis to the problem of jack platen indentation. Here an indentation factor was determined to estimate the uniaxial compressive strength (e.g., Prowse *et al.* 1990).

Using the borehole jack to measure strain modulus or *stiffness* has received little attention. In general, examination of the initial P-δ response in terms of strain at the borehole wall reveal strain moduli which are approximately an order of magnitude less than that expected. Demuth and Prowse (1992), however, suggest that a number of *ice indentor deformation moduli* (strain modulus indices) can be defined from the initial (pre-yield) P-δ response. Results, for columnar-grained freshwater ice, indicated that the relationship between these moduli and ice porosity, for example, is very similar to those derived from theoretical considerations (e.g., Assur 1967) and standard determinations of effective strain modulus and porosity (e.g., Trätteberg *et al.* 1975). Therefore, like jack strength, ice indentor deformation moduli hold considerable promise as a useful index of strain modulus. As noted by Demuth and Prowse (1992), however, additional data must be collected to corroborate the validity of these relationships for a wider range of indentation rate, ice temperature and ice structure.

Profiling in thin ice

To achieve a yield condition for strength measurement purposes, deformation rate must be sufficiently high and necessarily correspond to that occurring in nature during ice-cover failure (e.g., $\dot{\epsilon} \approx 10^{-2}$-$10^{-3}s^{-1}$ for dynamic break-up). At such deformation rates, however, the *test volume* at full jack indenture is extensive and therefore, only a single test is possible in one vertical borehole through most typical river ice cover thicknesses (< 0.75 m). As useful as such depth-integrating tests are, the significance of vertical inhomogeneities cannot be specifically evaluated. Notably, inhomogeneities produced by radiation-induced deterioration processes can cause important vertical variability influencing the flexural behaviour of pre-break-up ice covers (e.g., Demuth and Prowse 1991a).

Flexural fracturing and fragmenting is typical of ice sheets during river-ice break-up (e.g., Beltaos 1990, Demuth and Prowse 1991b). Although the jack test measures primarily compressive properties, Demuth and Prowse (1992) have shown that a vertical series of shallow indenture jack-tests can be used to vertically profile ice stiffness and thus assist in characterizing the flexural behaviour of the cover.

The above methodological advances are commensurate with hardware related advances (described below). Other methodological-hardware advancements, some of which have not yet been fully tested, have been developed in concert with the advancement of uniaxial testing vis-a-vis the control of load and displacement paths. These too are described next.

Hardware

Indentor actuator head

The current NHRI borehole jack indentor system incorporates the twin-actuator, National Research Council Canada (NRCC) indentor head (Figure 2). Each platen is capable of being instrumented for load and displacement. The current mechanical configuration of the NRCC jack head, however, does not permit simultaneous displacement and load measurements and thus load is inferred from actuator pressure records. Displacement of each platen is measured by an AC linear voltage differential transformer (LVDT) assembly. For the thin-ice profiling work described above, the concept of using a large backing plate in place of one of the actuators has been considered. The backing plate is machined to conform to the borehole geometry and unlike other previous borehole jack systems, contains a load cell to measure platen load directly (Figure 3).

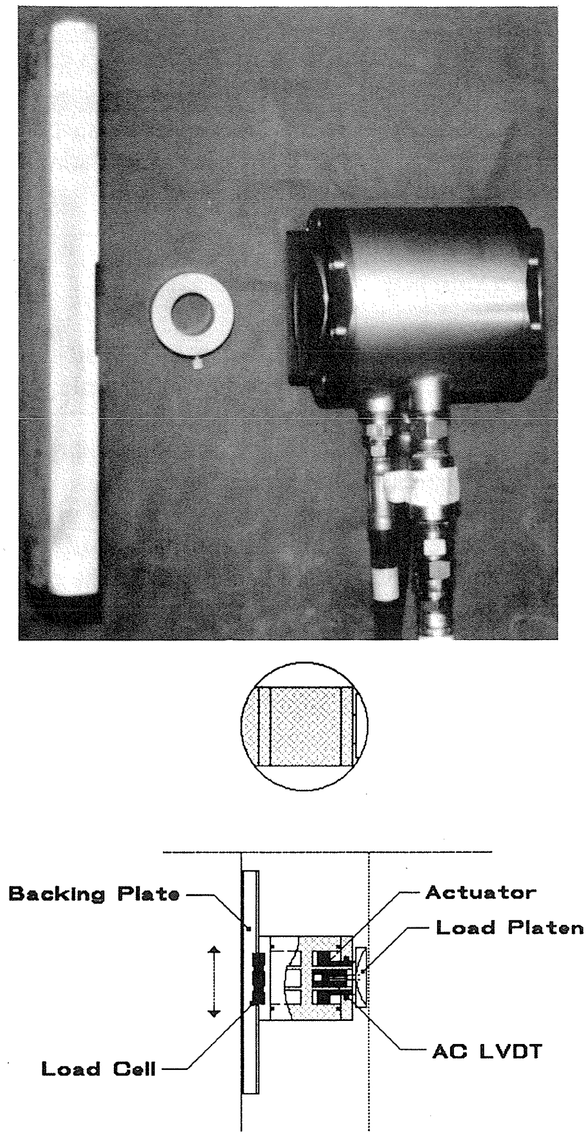


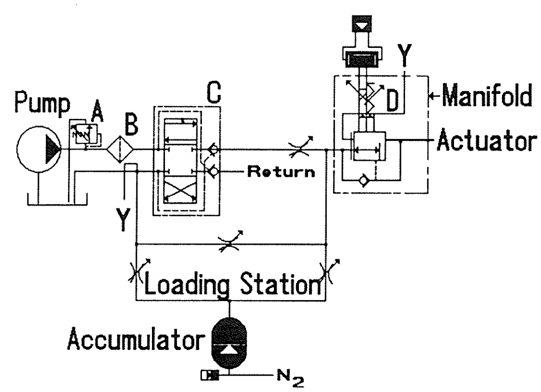
Figure 3 Schematic and photo of twin actuator jack with backing plate and load cell configuration for profiling operations.

Because the goal in thin ice profiling operations is to measure vertical stiffness variations, limiting the overall platen travel to that allowed by a single actuator poses no disadvantage, since it is the pre-yield P-δ characteristics which are of interest.

Load and displacement control systems

The initial river ice tests performed by the authors in 1987 utilized the Fenco jack (Kivisild 1992) and a hydraulic system which incorporated a simple directional valve to indent and retract the jack platen. The deformation rate was determined simply by ice response and the pressure-volume (P_p-V) characteristics of the hydraulic pump. Because the actuator pressures during testing in typical pre-break-up river ice covers are considerably lower (≈25 MPa) than those experienced in cold intact sea ice, a variety of moderately priced hydraulic controls could be used.

Following work by Gerome (1987), who used a simple restrictive flow control to exert limited but effective regulation of the NRCC jack indentation rate, the authors incorporated a pressure-compensated proportional flow control (Figure 4 bottom). Nominal displacement rate control has improved some 10-20% depending on the nominal rate selected and the condition of the ice. The flow control also featured an anti-lunge circuit to prevent initial indentation flow surges caused by the action of the pressure compensator. Further improvements were realized by fitting an accumulator/loading station to drive the test and provide what is effectively a *controlled displacement-path test*.



A Pressure Relief Valve
B Filter
C Directional Valve
D Proportional Pressure Control
E Pressure Compensated Flow Control

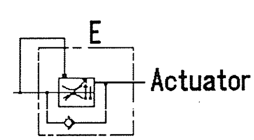


Figure 4 The NHRI indentor hydraulic control system with the proportional pressure control.

Additional utility of the jack can be achieved by the introduction of other hydraulic controls through a universal manifold. For example, a flow-compensated electrically-proportioned pressure control (Figure 4) can be mounted to effect a variety of *controlled load-path tests* such as a "constant loading-rate test" or an "indentation creep test", whose methodologies are analogous to those of the uniaxial variety.

Since the above systems still exert a form of open-loop control, unwanted variations in load and displacement paths can result because of inherent hysteresis and limitations in their static and dynamic response/accuracy. A relatively inexpensive servo-control system is available on the NHRI test rig to further improve control of the load-displacement path. Feedback is provided to a servo-amplifier by analog outputs generated at the digital data acquisition equipment which records the load-displacement history. This configuration is currently being evaluated.

Data acquisition and control

Data acquisition and control for the present NHRI test rig consists of a modular 32 bit digital system incorporating a variety of analog input signal conditioners and digital data storage devices. The system can operate stand-alone using ROM or accepts commands down-loaded from a field-portable computer (Figure 5).

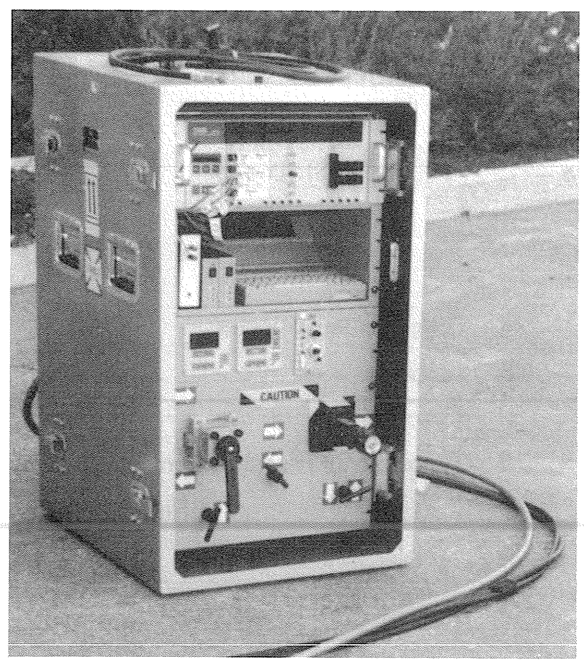


Figure 5 Field configuration of test rig. Test rig and core barrel fit through ambulance doors of Bell 206-L.

Software developed at NHRI allows the user to define a variety of parameters including acquisition rate, gain, control signal generation and feedback signal routing. Test identification and other details can also be input, and echoed output made to hard-copy devices, such as multi-axis plotter beds or strip chart recorders. All instrumentation operates on laboratory quality 117 VAC provided by a DC-AC converter and a 12 VDC battery, thus isolating the instrumentation from hydraulic pump/generator effects.

CONCLUSIONS

This paper has outlined recent methodological and hardware advances made to the borehole jack test at NHRI. How these advances have improved the utility of the jack test for *in-situ* ice testing in general and in particular, for characterizing the mechanical properties of pre-break-up river-ice covers, has been described. Although the structural characteristics of the pre-break-up river ice regime have led to the development of the methods and hardware described, such ice is not unique to the river-ice environment and it is hoped that these advancements will be transferred and utilized in other ice-related fields.

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