A NEW GENERATION OF FRAZIL ICE FIELD MEASUREMENTS

by
Arnold M. Dean, Jr.
Dean Consulting & Research Associates, Inc.
P.O. Box 1188, Koch Road
Norwich, VT 05055 USA
(802) 649-2202

Pierre Desroches
Hydro-Quebec
Service Hydraulique Division Hydrometrie
Place Dupuis
885 est, rue Sainte-Catherine
Montréal, PQ H2L 4P5 Canada
(514) 289-5528

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ABSTRACT: The DCRA modified impulse radar system and data processing equipment were used to acquire and analyze the GPR profiles. These profiles were used to locate prospective sites for performing tests of frazil ice characteristics. The mechanical strength of the frazil ice with depth was measured using a shear vane, a cone penetrometer, and an inflatometer (expanding bladder). The reacting forces from the shear vane and the cone penetrometer were measured using strain gages. The hydraulic flow beneath the frazil was measured by an electromagnetic flow meter. All data were recorded using a 16-bit digital audio tape (DAT) recorder. The frequency characteristics of the flow were determined. Various sample tubes were used to acquire samples of the frazil with depth. Large-diameter samples were used to investigate the area of influence from the cone and the vane, by taking sections of the sample and using thick-section techniques to identify the stressed areas within the frazil matrix. The density and porosity of the frazil with depth was determined by comparing the saturated and drained weights of the frazil sample. Particle size distribution was measured using a dimensioned grid and stereographic techniques. Expansion of the topics discussed in this paper may be found in DCRA Report 201.91, dated October 1991.

KEY WORDS: Frazil ice, Field instrumentation, Strength characteristics, Impulse radar, Cone penetrometer, Shear vane, Flow characteristics.

OBJECTIVE: to develop field techniques to acquire precise data characterizing the strength of frazil ice accumulations, and to document the conditions under which the data were acquired.

BACKGROUND: Up to the present time, hydro-power generation projects in cold regions were successfully studied and carried out. However, the needs for optimization of the uses of energetic and financial resources for reliable means of prediction and control of environmental impacts, and the use of modelling, especially numerical modelling, have dramatically grown. In our field of work, this had emphasized the needs for more accurate definition of the characteristics of the ice regime associated with a project, particularly, of one of its more important components, the frazil accumulations.

For many years the study of frazil ice has both intrigued and challenged the ice engineer. Very few materials are studied so close to the solid/liquid phase point. In addition, there are no materials having the void ratio of frazil accumulations which have so great a cohesive bond among the particles.

It is difficult, if not impossible, to generate large quantities of frazil ice under laboratory conditions with the current facilities available. This is particularly true when one tries to generate and deposit these accumulations in such a way as to model field conditions. One is, therefore, required to go into the field in order to study the mechanical properties of frazil accumulations.

Precise data acquisition in the field has always been a problem. This is certainly the case when the parameters to be measured are so sensitive to the measurement techniques.

So far as the author knows, up to the present study, all field measurements have been made mechanically and recorded manually. This work was proposed and initiated with the intent of acquiring more precise data describing the mechanical properties of frazil ice, while characterizing the physical properties of the ice and hydraulic conditions at the sites.

Mechanical tools, such as the shear vane and cone penetrometer, which have been used in the past to characterize the strength of the frazil ice accumulation, have relied on standard soil mechanics interpretations of the analyses. It was suspected by the author for a number of years that both the shear vane and the cone penetrometer had areas of influence greater than their diameters. No data had existed to support this contention.

Location: Hydro-Quebec located two different sites at which studies could be conducted. It would have been preferred to make many trips to these sites throughout the winter in order to more closely monitor the progression of the ice conditions. This was not feasible. We were, however, able to acquire data at three different periods at the Melocheville site on the St Lawrence River. The upper site on the Grande Baleine River was studied on only one trip.

The site on the Grande Baleine River is located just upstream from the proposed GB-2 dam site. The study area is slightly upstream of the confluence of the Laguerne Riviere and the Grande Riviere de la Baleine. The reach is some 2.5 to 3 Km down from the first of several rapids reaches. Frazil having been generated in the rapids is deposited into the study reach. The hydraulic conditions in this area was not known. The water on the surface ran down to the site and primarily around, along the right bank (due to the higher topography of the sheet ice in the middle of the site—as supported by grounded frazil accumulations).

The second site was located near Melocheville, PQ, which is on the southern bank of the St Lawrence river southwest of Montreal, and slightly to the west of the Beauharnois canal. The survey area consisted of 5 lines each 200 meters running longitudinally to the flow, and 5 transverse lines. In addition, the center line was extended upstream some 300 meters.

These two sites were significantly different. The Grande Baleine site is typical of a high-flow river reach where significant frazil is generated at the beginning of the season and a channel meanders through the frazil. Whereas, the St Lawrence, being a much larger river with a significant variation in the bottom topography, illustrates an area where a channel runs near a shallower region. In the St Lawrence reach there were several runs of frazil followed by periods of hydraulic compaction of the lower part of the accumulation. These resulted in significant layering within the accumulation. Some layering was seen in the Grande Baleine site, but not on the same scale as the St Lawrence site.

FIELD EQUIPMENT AND TECHNIQUES

Impulse Radar: The DCRA modified impulse radar as used in profiling of snow, sheet ice thickness and frazil accumulations by snowmobile. Figure 1, taken from the sled, shows the radar equipment with the 250 MHz antenna trailing behind. A typical profile is seen in Figure 2. Profiles included areas with over a meter of snow and of sheet ice, and up to 15 meters of frazil ice. In some cases the time window allowed one to see the river bottom, and in other cases the sub-bottom could be seen. Layering in the frazil ice was observed, as well as hydraulic compaction between the frazil ice and the main channels of flow.

Shear Vane: The shear strength of the frazil ice was measured by using a typical soils mechanics shear vane. The vanes were 7.5 cm and 15 cm in diameter by 15 cm in length. Extension rods were used in order to place the measurement at the appropriate depth. Various drive mechanisms were used to turn the vane in the frazil. Figure 3 shows the basic configuration of the test. In this set-up, the operator is turning the shear vane by hand. In other tests, a

90:1 speed-reducer gearbox was driven either by hand or by a variable-speed drill, so that accurate angular measurements could be made. The gearbox could swing away from the shear vane stand, as shown in Figure 4, in order to attach additional rods as well as the torsional strain gage. Figure 4.1 illustrated data from this instrument.

Cone Penetrometer: The cone penetrometer was pushed down into the frazil ice by a drive plate traveling on the worm-gear mechanism shown in Figure 5. The traveling plate held the compression strain gage, which was attached to the cone extension rods. The variable-speed electric drill turned the worm gear. The cones used in the penetrometer are standard 45° and 60° cone, having a base diameter of 5 cm. Typical results from this device are seen in Figure 5.1.

Inflatometer: The principle of the inflatometer is similar to that in soil mechanics. The particle size and porosity of the frazil, however, require that the ratio of the ending radius to the starting radius be much greater than for soils. Considerable effort, therefore, was made in material selection and devising an expanding bladder so that a symmetrical expansion under these conditions could be attained. The mechanism for this test is seen in Figure 6, where the expanding bladder is shown sequentially in the lower left of the figure. The bladder is expanded by an introduction of fluid from the pressurized fluid reservoir. The sequence of the test is to introduce, in an incrementally-increasing fashion, air pressure on the fluid in the reservoir. As a pressure is maintained, the fluid flow into the bladder is monitored with time. This allows the development of a relationship between pressure and volumetric change. When the test was completed, the inflate valve was closed, and the deflate valve was opened, and the fluid was hand-pumped back into the reservoir. Figure 6.1 shows results from this test.

Water Velocity Profile: The sensor for the electromagnetic flow meter generates an electromagnetic field which is distorted in proportion to the flow velocity past it. This is a very sensitive instrument, and can provide significant insight into the bandwidth of the forces acting on the accumulation. The monitored distortion was recorded on the DAT in order to attain a measure of the frequency distribution of the flow at various points in the hydraulic transition zone beneath the ice. The equipment is seen in Figure 7. Figure 7.1 shows the frequency response at one point in the hydraulic transition zone beneath the ice.

Frazil Sampling: Frazil sampling with depth was done using a sample tube designed by the author. There is a one-way valve in the top of the sample tube which allows the water over the sample to exit the tube, and also holds a suction when the sample is taken out of the water and onto the sheet ice. These samples were used in order to get density measurements and particle size distribution with depth.

Density measurements were computed using fixed-volume frazil samples. A comparison of the weights when saturated and drained provides the accumulation density and porosity.

One of the more critical measurements involved acquiring large-diameter frazil samples in order to determine the area of influence within the frazil due to the penetration of the cone, or the turning of the shear vane. A large-diameter bulk sampling tube was used for this measurement, but depths were limited to just below the 1 meter-thick sheet ice.

Particle size distribution was obtained with depth by throwing portions of the frazil from the sampling tube onto a grid. Measurements were taken using standard stereology procedures.

ANALYSIS

Radar: The impulse radar was used to identify areas that represented characteristic frazil accumulation, such as reasonably homogeneous frazil areas, where there was significant layering within the frazil body, and severely compacted frazil above flow channels. The radar profiles were also used to locate the main water channels, and to identify areas where mechanical samples should be taken, as well as flow measurements beneath the frazil should be made.

Shear Vane Measurements: The area of influence of the shear vane was determined by taking thick sections of bulk-sampled (and stabilized) frazil about the vane, back-lighting the wafer, and investigating the regions where the frazil matrix was disturbed. An example of this is seen in Figure 8. As the figure illustrates, the ratio of the effective radius to the actual radius varied between 1.2 and 1.4. The consistent acquisition of undisturbed large samples with depth is quite tedious. Because the area of influence is affected by the frazil density, significant effort in developing a sampler would be helpful if the shear vane is to be used in wide-spread field measurements. The data from a test was shown in Figure 4.1. Note that there are intermediate compaction regions as the torque is steadily increased towards the failure angle. This characteristic seems to be inversely proportional to the density of the accumulation. More study is recommended on the progressing shape of the area of influence as the vane is turned.

Cone Penetrometer: The area of influence within the frazil accumulation by the cone penetrometer was determined using a back-lighted thick section, as in Figure 9. From our measurements, the effective radius is much less sensitive to the density of the frazil. The cone appears to develop a reasonably stable "ice prow" which precedes it down through a naturallydeposited accumulation. We suspect that this prow is changed when the cone is pushed through severely compacted frazil, such as is found over a high-flow channel. The results of a cone penetrometer measurement was seen in Figure 5.1. This device can provide a continuous profile of the strength of the accumulation, and it appears not to need extensive companion density data. The cone penetrometer provides a reliable strength indicator. Further investigations are recommended so that a true strength measurement can be developed.

Inflatometer: The use of the inflatometer in these tests provided significant insight into the mechanical and energetic properties of frazil ice accumulations. In particular, it identified a yield characteristic which had not been observed previously. Figure 6.1 shows the energy expended as a function of radius, as well as a time plot of the yield property exhibited in one set of tests. This supports our intuition of the rate-dependence of frazil ice strength.

Flow Meter: With its wide bandwidth, the electromagnetic flowmeter still provides the premiere flow investigation technique in determining the flow characteristics beneath an ice cover. Such data as that obtained in this work open new perspectives for the analysis of the stress on the bottom of the ice. The energy distributed in the spectrum shown in Figure 7.1 provide a complex pulsation of force. Consider the typical velocity-versus-depth curve used to determine the shear on the bottom. This pulsation effectively takes the curve by the lower region and whips it up closer to the ice, providing periods of stress much higher than we normally recognize. This is an extremely timely and interesting area to pursue in future fieldwork.

Temperature, particle size distribution and accumulation density: These measurements were taken in the field but not included in this paper. The reader may contact the authors for further information in this area.

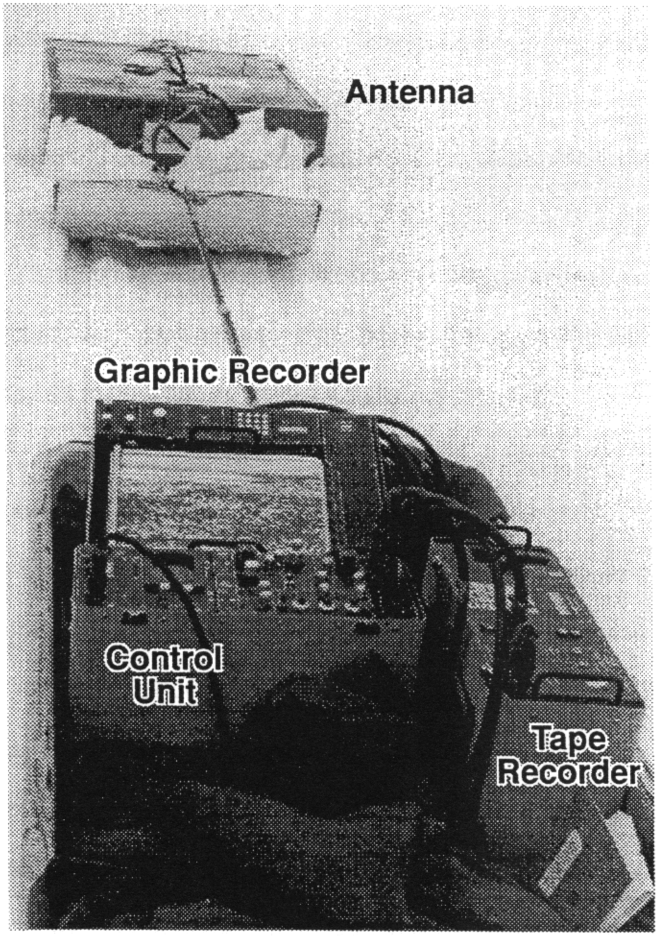


Figure 1: Radar equipment in the sled consists of the control unit, graphic recorder and tape recorder. The control unit sends timing information to the antenna. The antenna sends a high-power impulse into the media and receives the reflected energy. The return is sent through the control unit to the tape and graphic recorders.

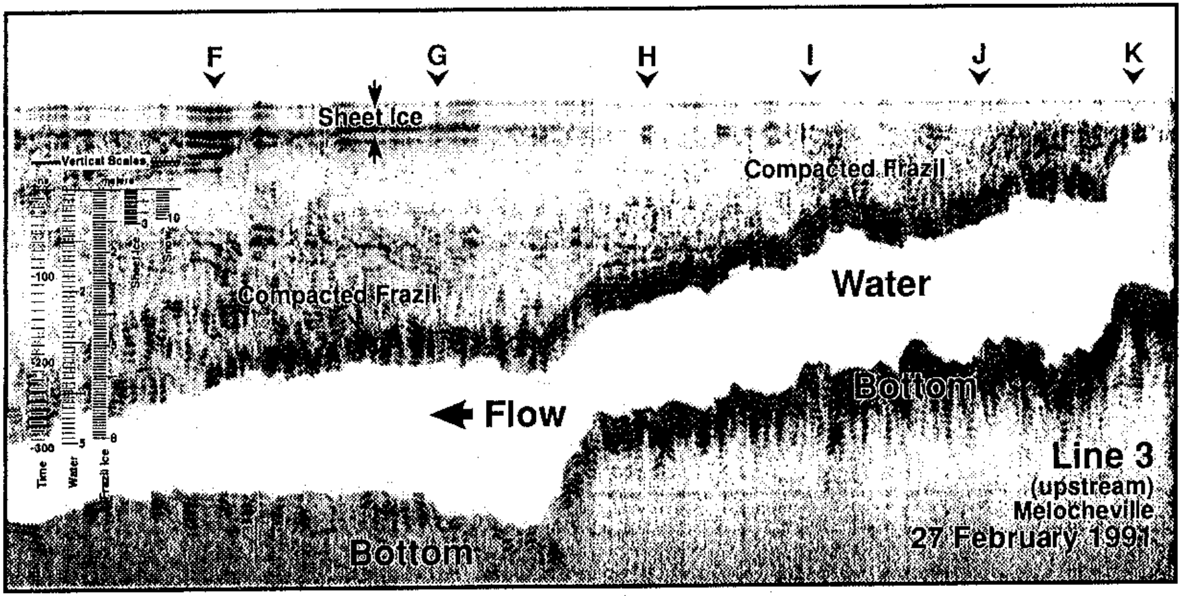


Figure 2: Example of radar profile over frazil ice accumulation showing layered and compacted frazil regions. The compaction band in the lower frazil boundary upstream is due to hydraulic stress imparted by the flow.

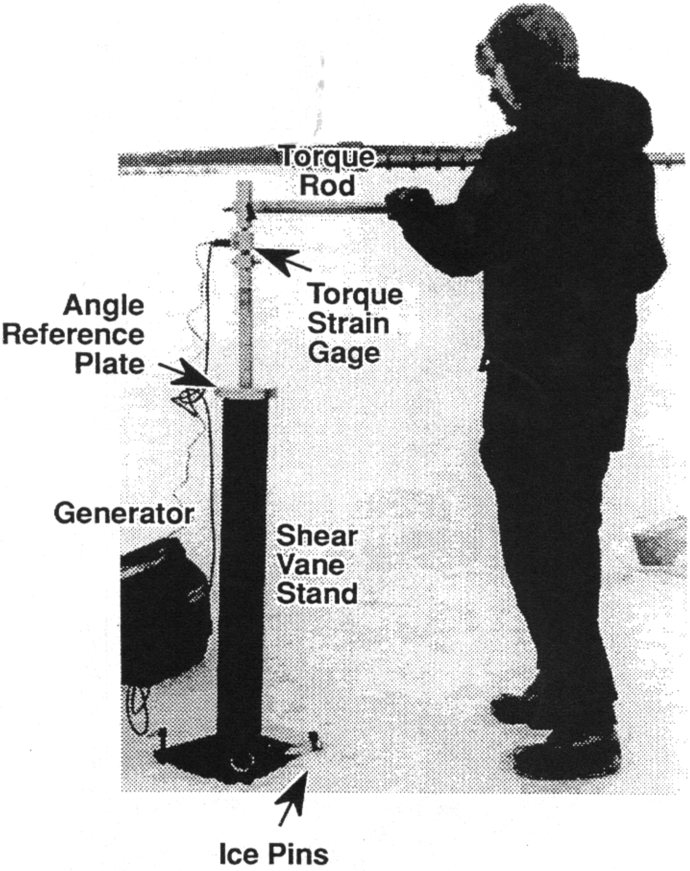


Figure 3: The shear vane was attached to its extension rods and placed at the depth of interest in the frazil. The shear vane stand acts as a guide, while the operator turns the shaft with an extension rod. The torque presented to the shaft by the frazil about the vane was measured by the torsional strain gage, and recorded by the digital audio recorder (DAT).

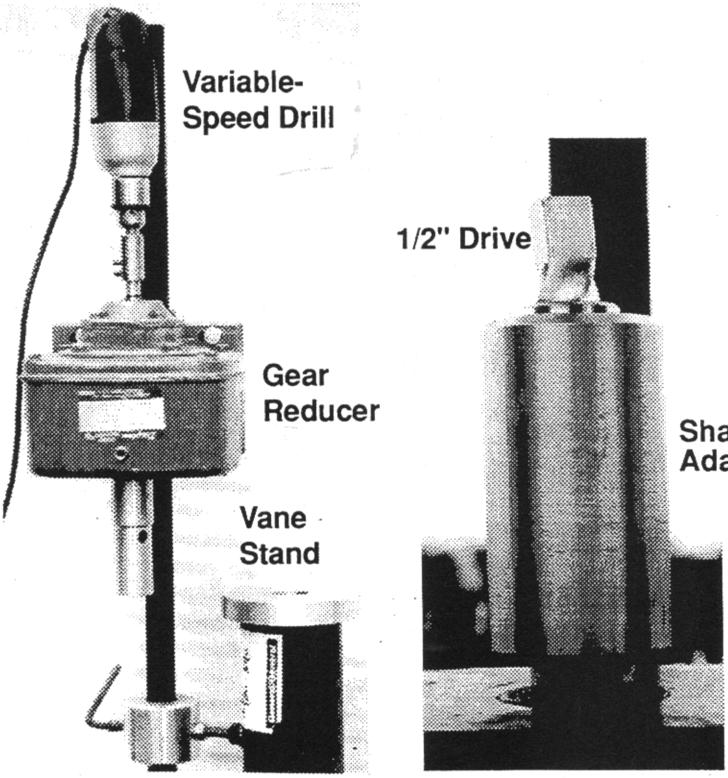


Figure 4: The 90:1 speed reducer is used as an angular displacement reducer in order to more precisely associate angle and strain measured. The speed reducer could be raised on the guide rod as well as swung away from the stand in order to attach extension rods. There was an occasion when the frazil ice was strong enough to fail a 1/2-in aluminum drive shaft on an adapter, as seen in this figure. This is a typical example of how strong a shear response can be in highly compacted frazil.

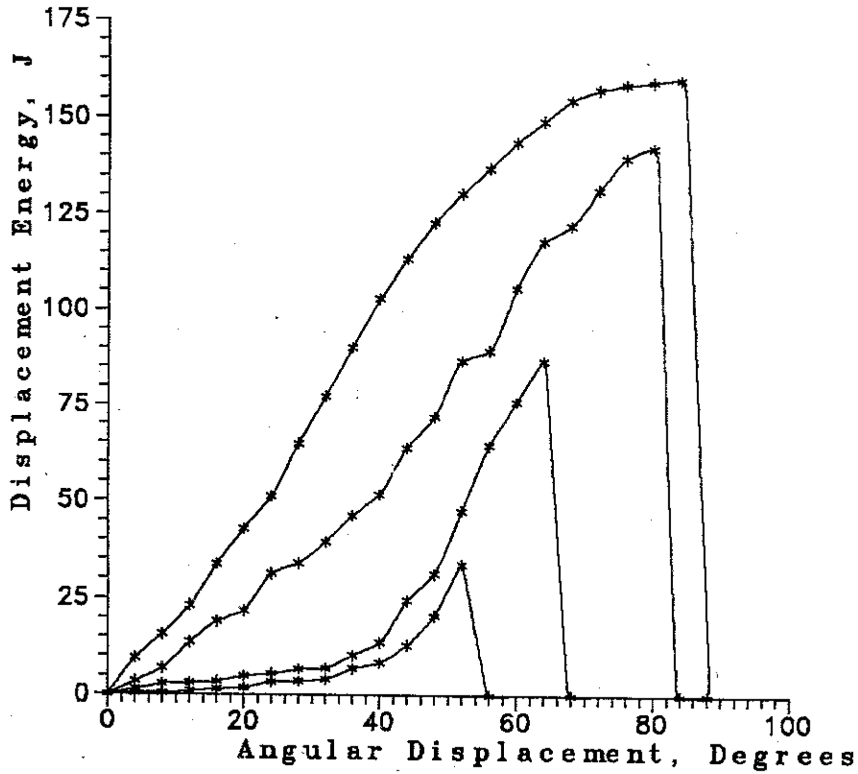


Figure 4.1: Stress imparted to shear vane as a function of angular displacement.

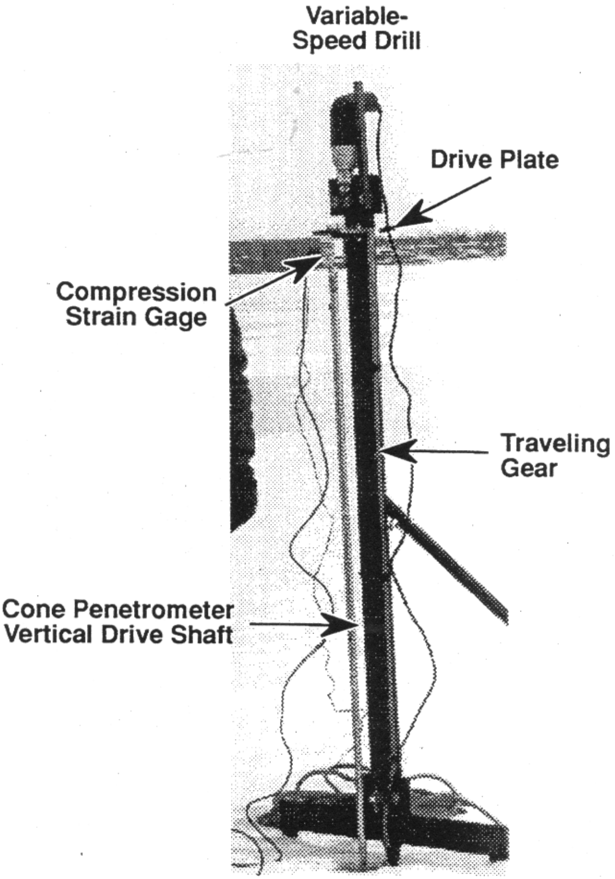


Figure 5: Cone penetrometer mechanism. The worm gear is turned in place by the variable-speed drill. The traveling platform is moved along the length of the running gear. Attached to the platform is the compressional strain gage. Extension rods and the cone are attached to the strain gage. The output of the strain gage is recorded on the DAT.

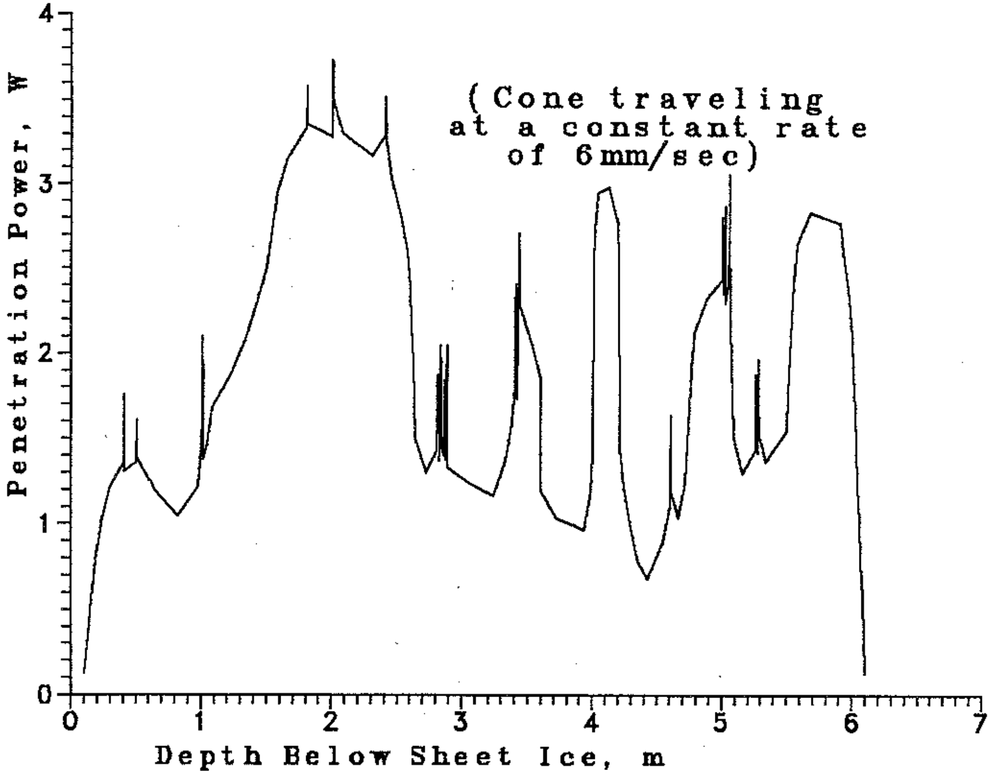


Figure 5.1: Stress imparted to cone penetrometer as a function of depth.

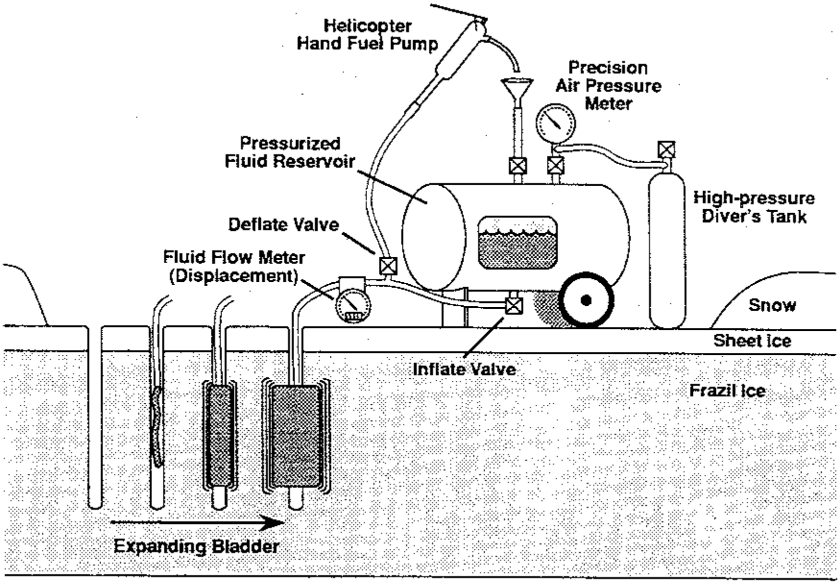
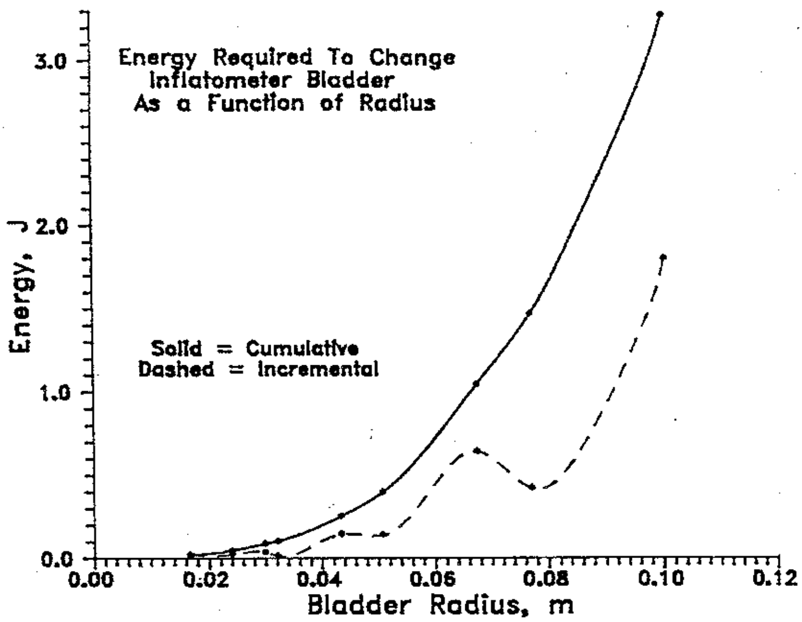


Figure 6: The inflatometer test setup. Air pressure was incrementally increased in the pressurized fluid reservoir. As the pressure was maintained at a fixed level, the flow was monitored into the bladder until the change in flow was negligible. The pressure was increased to a higher level, and the flow was again monitored. When the bladder was completely, the inflate valve was closed and the inflate valve was opened. The fluid from the bladder was then pumped back into the reservoir.



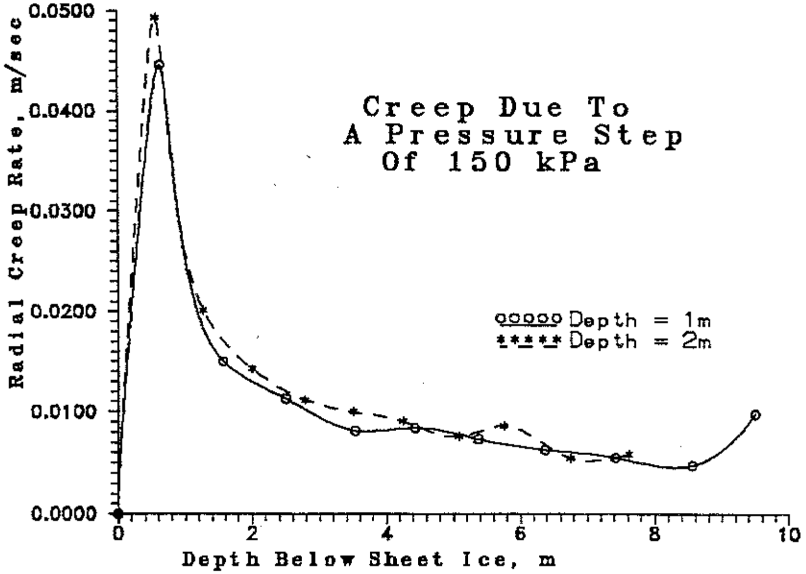


Figure 6.1: (Upper) Energy associated with the change in bladder radius. (Lower) Frazil ice creak rate due to constant stress imparted by the bladder.

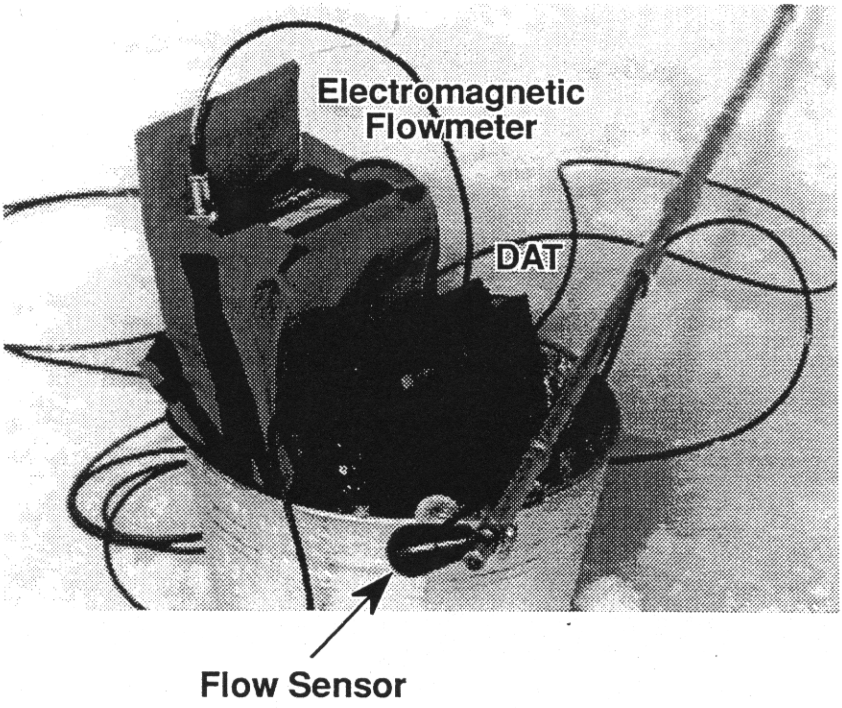


Figure 7: The electromagnetic one-dimensional flowmeter whose output was recorded on the DAT.

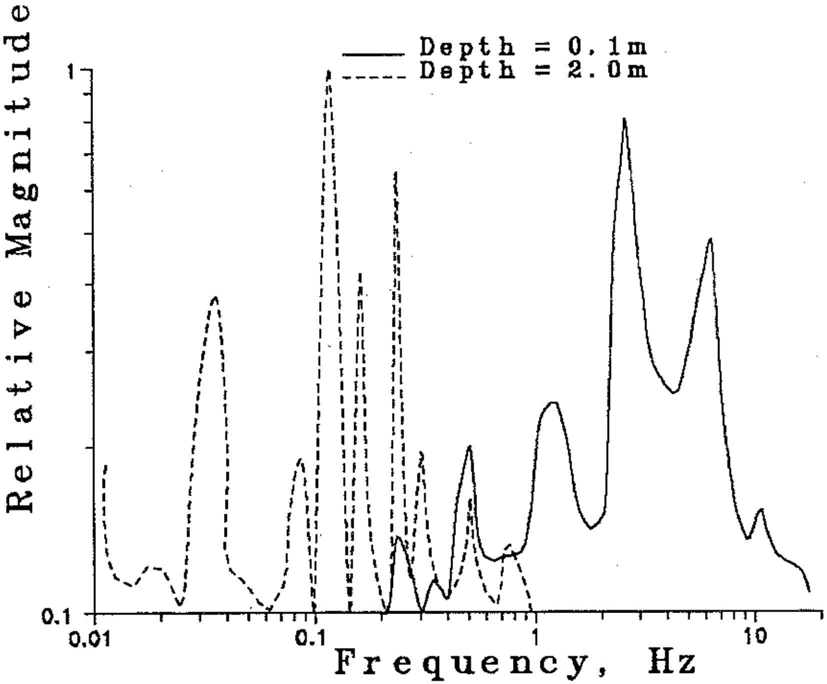


Figure 7.1: Frequency spectrum as measured by EM flow meter at one and two meters below frazil ice.

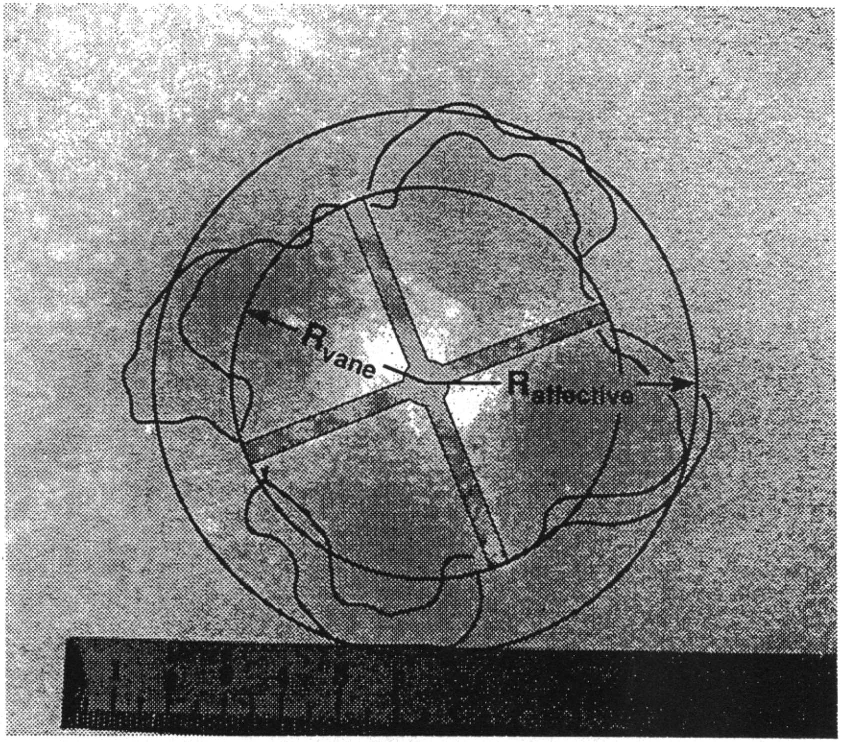


Figure 8: The area of influence of the shear vane was determined by visually identifying the stressed areas about the vane as it incrementally turned through fixed angles. One can observe in this sample the difference between the effective radius of the shear vane and the actual radius. This significantly complicates the evaluation of shear vane data.

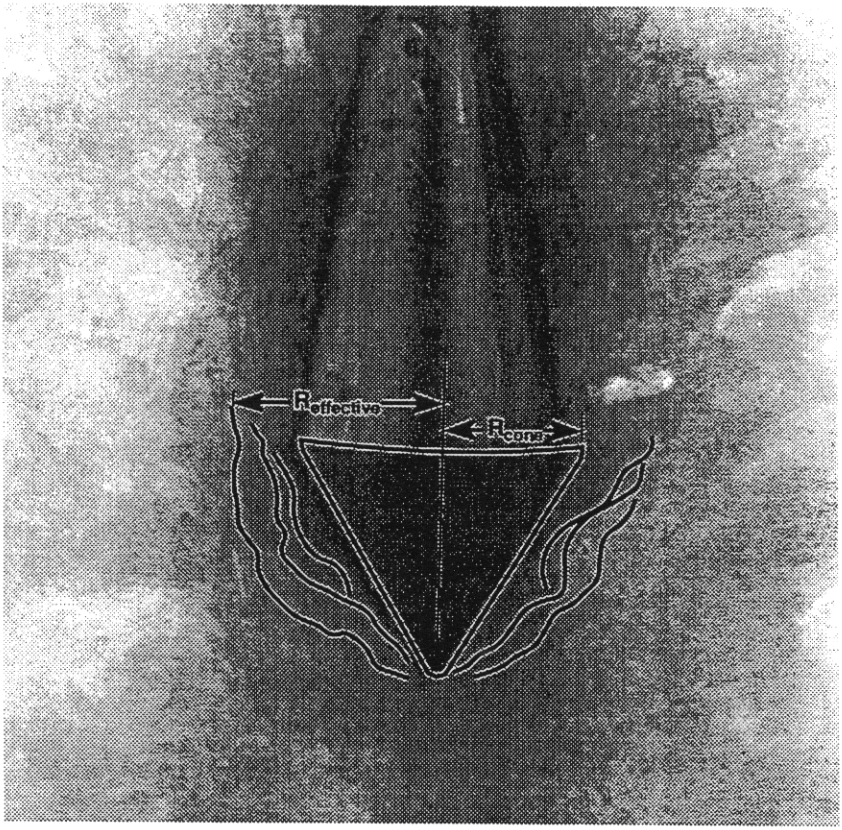


Figure 9: A vertical thick section is taken of the frazil with the cone penetrometer. The area of influence is then outlined using the backlighted technique.