CRREL REPORT 92-7

AD-A255 410

(2)

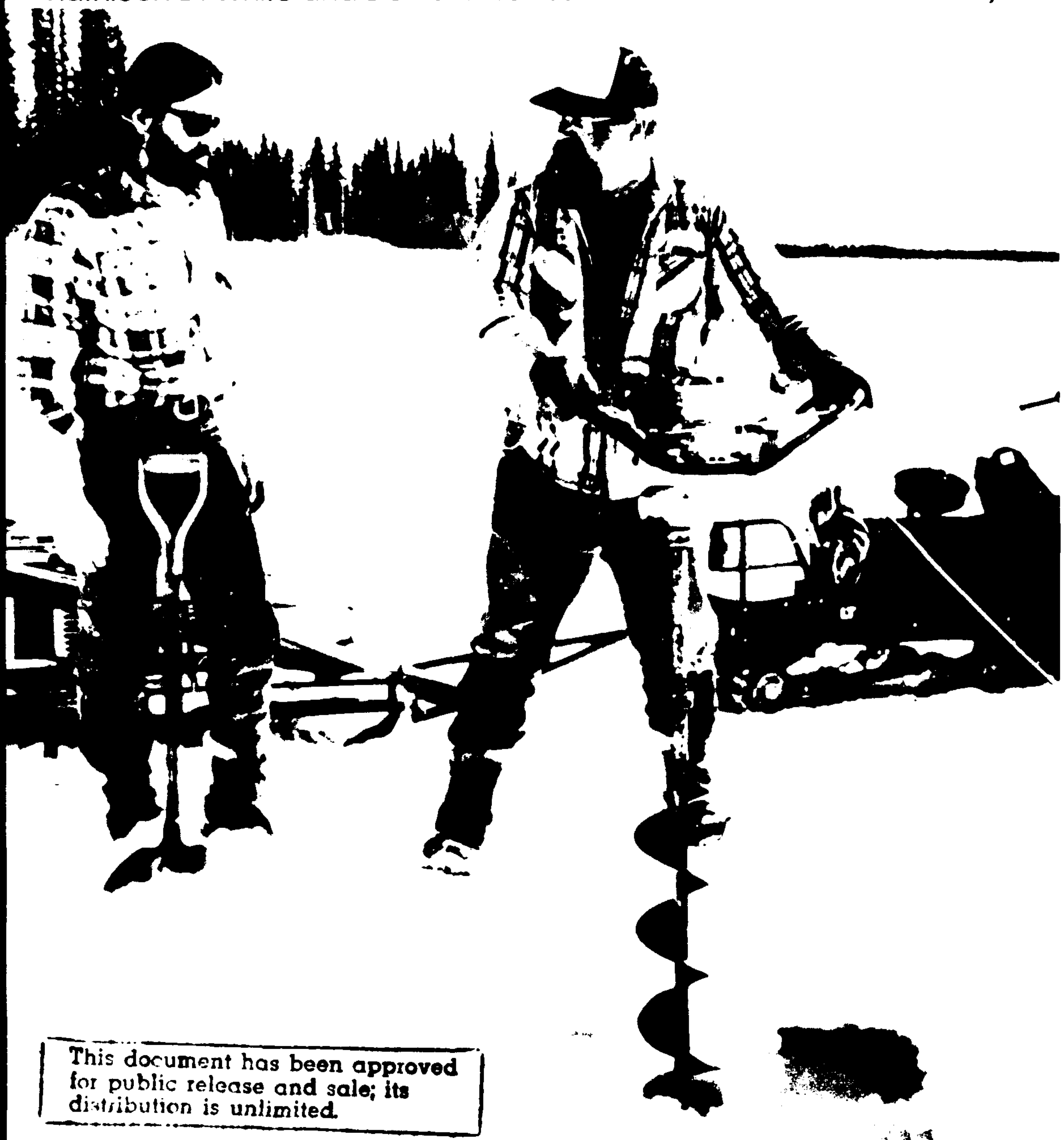
CRREL

Determining the Intrinsic Permeability of Frazil Ice

Part 2: Field Investigations

Kathleen D. White and Daniel E. Lawson

May 1992



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Drilling hole for borehole dilution tests on Tanana River, near Fairbanks, Alaska. (Photo by K. White.)

CRREL Report 92-7

U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Determining the Intrinsic Permeability of Frazil Ice

Part 2: Field Investigations

Kathleen D. White and Daniel E. Lawson

May 1992

Accesion For		
NTIS CRA&I		☑
DTIC TAB		☐
Unannounced		☐
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

PREFACE

This report was prepared by Kathleen D. White, Research Hydraulic Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, and Dr. Daniel E. Lawson, Research Physical Scientist, of the Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. This work was funded by the CRREL In-house Laboratory Independent Research Program under the work unit, *Field Measurement of Seepage Velocity in Frazil Ice*.

The authors are particularly indebted to Bruce E. Brockett, who was invaluable in conducting the field test and who contributed to the report graphics. They are also grateful to the CRREL-Alaska office personnel, especially Judith Smith and SFC David Dillingham, for their support during field experiments. Dr. Thomas P. Ballestero also provided helpful advice. Dr. George D. Ashton and Steven F. Daly provided technical review. In addition, the authors express their appreciation to Donna Harp for her word processing support and to Edward Perkins, William Bates and Matthew Pacillo for their work on the figures.

CONTENTS

ILLUSTRATIONS

TABLES

Determining the Intrinsic Permeability of Frazil Ice
Part 2: Field Investigations

KATHLEEN D. WHITE AND DANIEL E. LAWSON

INTRODUCTION

Although frazil ice causes problems in many northern rivers, physical parameters of frazil deposits are not well known. The intrinsic permeability and the related hydraulic conductivity of a frazil deposit are two such parameters for which few data exist. The intrinsic permeability parameter describes the capacity for flow through the solid matrix, while the hydraulic conductivity relates the properties of the fluid to the intrinsic permeability of the solid matrix. They are related through the Nutting equation:

$$K = \frac{k \rho g}{\mu} \tag{1}$$

where K = hydraulic conductivity
k = intrinsic permeability of the solid
g = acceleration due to gravity
μ = dynamic viscosity of the fluid
ρ = mass density.

The porosity of the material is often used in estimating the volume of ice in the deposit and can be approximated from the intrinsic permeability.

There are no existing in-situ field methods for determining the intrinsic permeability of frazil deposits. In the past, this parameter has been estimated using a permeameter test which cannot be performed in situ and modifies the frazil ice during sampling. The borehole dilution method, which was developed as a nondestructive test to measure groundwater velocities, has been used to determine hydraulic conductivity in soils. A laboratory investigation of the applicability of the borehole dilution method to frazil deposits showed that this method held some promise for use in determining frazil permeability in the field (White 1991).

This report describes the application of the borehole dilution method to frazil ice deposits in the Tanana River at Fairbanks, Alaska. We also compare borehole dilution data to correlative in-situ data from previous studies at this site. This technique proved to be a relatively straightforward field method for the in-situ determination of the seepage velocity and intrinsic permeability of a frazil deposit. The results of the tests suggest that it may be useful to indirectly describe deposit structure as well.

BACKGROUND

The intrinsic permeability of a material (k) is an overall measure of the characteristics of the solid matrix that affect permeability. These characteristics include the size, shape, size distribution and packing of the particles, the porosity of the deposit, and the tortuosity of the pores. The intrinsic permeability of a frazil deposit also reflects its internal structure. The intrinsic permeability of the deposit, as well as of individual layers, may be up to several orders of magnitude larger in the horizontal direction than in the vertical direction. Frazil deposits can consist of homogeneous, isotropic layers that have been deposited sequentially during discrete events. These layers are sometimes separated by a thin layer of less permeable material that may result from melting and refreezing of the deposit along its contact with adjacent flowing water during alternating warmer and colder periods.

In a saturated material, the intrinsic permeability describes the ability of the material to transmit fluids. Some knowledge of this parameter is necessary to model accurately the response of the material to loading. For example, one might wish to estimate the force necessary to push an indenter through a frazil deposit. As the indenter moves into the deposit, the structure of the ice matrix and the water within pores in the matrix resist movement. The displacement of the water, and thus its resistance, is controlled by the intrinsic permeability of the matrix.

DETERMINING INTRINSIC PERMEABILITY

In-situ methods for determining intrinsic permeability are preferred because it is difficult to sample frazil ice without considerable disturbance. However, neither intrinsic permeability nor hydraulic conductivity can be measured directly. They may be calculated from the seepage velocity (v) and the slope of the water surface using Darcy's law. For homogeneous, one-dimensional flow, Darcy's equation is

$$k = \frac{v\mu}{\rho g(dh/dl)} \tag{2}$$

where dh is the change in head over distance dl. Darcy's law assumes that flow is laminar. Flow regimes are generally described by the Reynolds number:

$$R = \frac{vd}{\upsilon} \tag{3}$$

where υ is the kinematic viscosity of the fluid and d is a representative length scale parameter, taken here to be the mean particle diameter. Laminar flow occurs in the region where the Reynolds number is less than 1, and flow is primarily laminar for Reynolds numbers less than 10. Most groundwater flows in soils are laminar (Bear 1979, Freeze and Cherry 1979). White (1991) found laminar flow in a frazil ice deposit formed in a refrigerated, hydraulic flume; however, Reynolds numbers have not been determined for flow through a natural frazil deposit.

Several methods exist for in-situ determination of the hydraulic conductivity and intrinsic permeability in soils, including piezometer and borehole dilution tests. Piezometer tests involve monitoring the water levels in a single piezometer following the instantaneous removal or addition of a known volume of water. The hydraulic conductivity of the soil is proportional to the ratio of inflow to, or outflow from, the piezometer and the difference between the initial head and the head at a given time. However, these tests require a time period of hours to days or longer in soils. While the time period might be shorter in a frazil deposit, the unsteady flow conditions in a laboratory flume or natural river, combined with difficulties in measuring small changes in head over a short time period, present obstacles to applying this test to frazil deposits.

In borehole dilution tests, the dilution of a tracer material introduced into a borehole is monitored over time. Intrinsic permeability and hydraulic conductivity can then be calculated once the seepage velocity is known. Lewis et al. (1966) present an expression convenient for determining seepage velocity from borehole dilution tests:

$$v = \frac{-\pi d}{8t}\left[\log\left(\frac{C}{C_0}\right)\right] \tag{4}$$

in which C = concentration of the tracer at time t
C_0 = initial concentration of the tracer in the borehole
v = groundwater velocity
d = diameter of the borehole.

This relation assumes that tracer dilution is a result of the horizontal movement of water through the borehole. Uniform concentration of the tracer throughout the borehole and steady uniform flow through the deposit are also assumed. In practice, the groundwater seepage velocity is found by plotting the log of the ratio of concentration at time t to the initial concentration vs time.

White (1991) used the borehole dilution test to determine seepage velocity through frazil deposits artificially formed in a refrigerated hydraulic flume. She measured dilution of the fluorescent tracer Rhodamine WT in boreholes cut to the deposit's center. Because the deposits had a relatively large change in head over a short distance, intrinsic permeability was estimated from seepage velocity using the Dupuit-Forchheimer approximation to flow through a saturated medium between two reservoirs. The average intrinsic permeability was 9.8×10^{-7} cm^2. The coefficient of variation for these tests was 32%, well within the normal range for this parameter when measured in soils (Nielsen et al. 1973).

Dean (1976) proposed measuring the intrinsic permeability of a frazil deposit in the field using a constant-head permeameter test, with 10W motor oil as the permeameter fluid. In his tests, frazil ice was sampled by pushing a cylinder (30.5 cm high × 8.9 cm in diameter) horizontally into the frazil deposits. The samples were then removed, oriented vertically and allowed to drain. During cold weather, the samples were spun to speed draining and decrease freezing within the sample. Once drained, the samples were placed within the test apparatus. The average intrinsic permeability obtained from two tests was 1.53×10^{-5} cm^2. This value is comparable to that of an unconsolidated gravel deposit (Freeze and Cherry 1979); the range of average frazil particle size was 2 to 5 mm.

Beltaos and Dean (1981) conducted further field investigations which included measuring the intrinsic permeability using the same permeameter method as Dean (1976). They reported values of 1.63×10^{-5}, 1.56×10^{-5}, and 1.50×10^{-5} cm^2 at depths of 2, 7.6, and 12.2 m below the base of the ice cover for frazil deposits with particle sizes ranging from 1 to 6 mm.

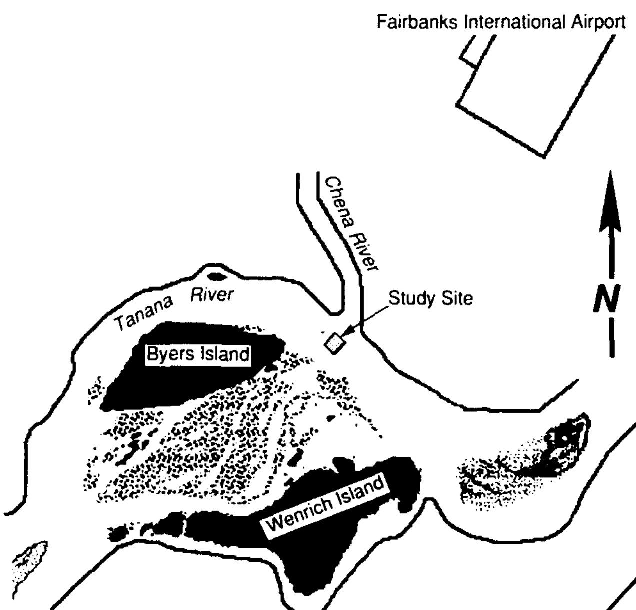
METHODS AND MATERIALS

Field tests of the borehole dilution method took place on the Tanana River, near Fairbanks, Alaska, in April 1991 (Fig. 1a). Eighteen boreholes were drilled along several short cross sections near the confluence with the Chena River (Fig. 1b). Frazil deposits in this area were previously studied in detail (Lawson et al. 1986a,b; Lawson and Brockett 1992), and provided baseline data for interpreting our test results.

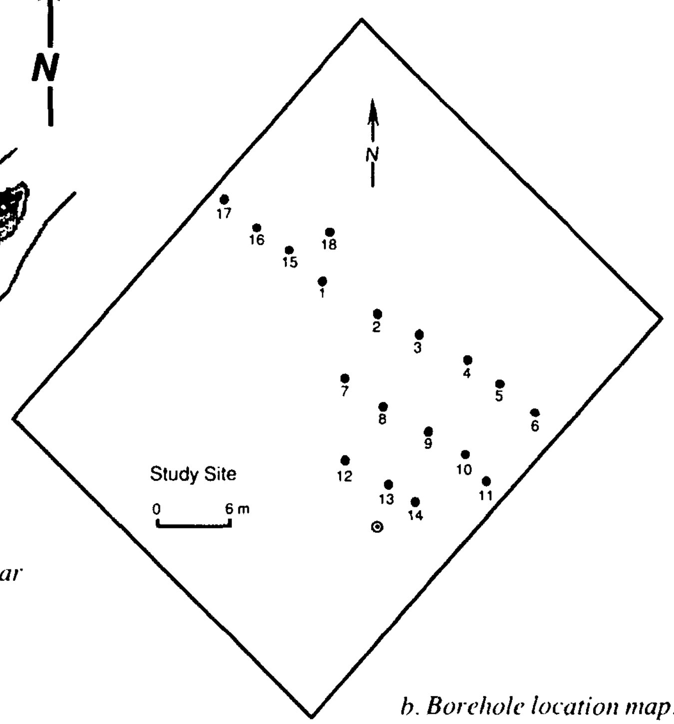
Boreholes were cut using a 5.1-cm-diameter CRREL ice auger with powerhead. The boreholes were partial-depth holes, extending to a point above the estimated bottom of the frazil deposit. The walls of each borehole were checked to be sure that the deposit was competent and that no large voids were present, because the manner in which the test borehole is formed can affect borehole dilution results. Packing or smoothing of the borehole walls during drilling, for example, would cause the walls to be less permeable than the surrounding deposit; dilution tests would then underestimate the seepage velocity and underpredict the intrinsic permeability. Hvorslev (1951), after extensive study of piezometers in soils, recommended that the walls of a piezometer or borehole be more permeable than the surrounding soils to avoid such effects. Unfortunately, the effects of augering frazil ice deposits with a CRREL ice auger are unknown; however, inspection of the boreholes suggested that coring had little effect on the deposit structure.

Each borehole was logged, primarily according to changes in resistance of the deposit during drilling or during probing with a rod pushed down the borehole into the deposit. Boreholes used for testing were numbered 3, 4, 5, 8, 9, 10, 15 and 18 (Fig. 1b), while the remaining boreholes were logged to better define the internal structure of the deposit. Water levels in each borehole were measured by leveling to establish the direction of flow and gradient. The average water slope during the test period was estimated from surveyed water levels to be about 0.00017, trending NNW (Fig. 1b).

For each test, the pump intake and one pump discharge tube were attached to a pole which was inserted into the borehole (Fig. 2). Each of these tubes was fitted with a screen to prevent frazil ice from plugging the ends. The discharge tube was approximately 10 cm



a. Study area.



b. Borehole location map.

Figure 1. Location of study on the Tanana River near Fairbanks, Alaska.

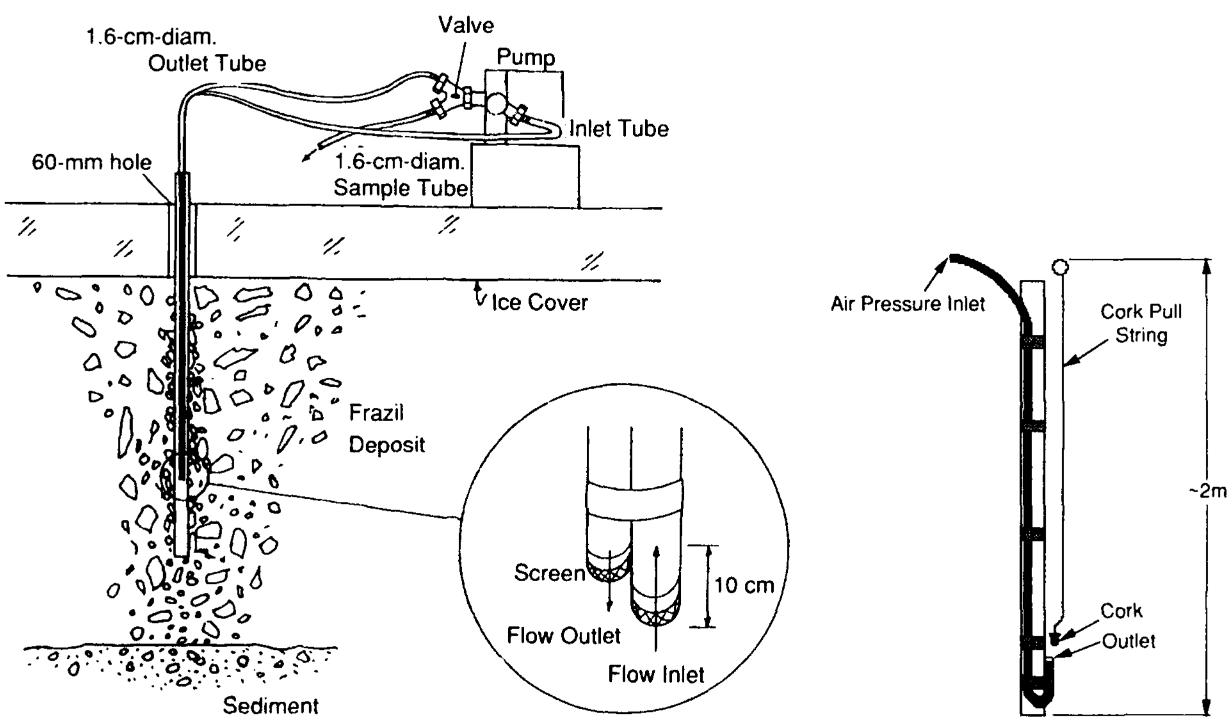
above the intake. A second pump discharge tube was used to collect samples. Both discharge tubes were connected to the pump outlet via a Y-shaped valve that controlled the amount of flow to each discharge tube. The valve was partially opened during sampling to allow some water through the sample tube. Otherwise, all flow was returned to the borehole. The pump was primed and a circular flow pattern established before the tracer dye was introduced.

Rhodamine WT, a fluorescent dye, was chosen as the tracer because of its lack of adverse environmental effects and because it is easily measured using a filter-type fluorometer. This dye is commonly used in borehole tests in soils as well as for measuring the discharge of rivers. Wilson et al. (1986) reviewed the operation of filter fluorometers with fluorescent dyes, including Rhodamine WT. White (1991) discussed the use of Rhodamine WT in cold conditions.

In the field, the Rhodamine WT solution was stored in the snow to equalize its temperature to near that of the water in the deposit. For dye injection, approximately 15 mL of 5000-ppm Rhodamine WT was added to the short end of the tubing (shown in Fig. 2b), which was then corked. The rod was then inserted into the borehole and the dye introduced by blowing into the left tube. At the same time, the cork was pulled with the attached string, the combined force being enough to remove the cork and release the dye. Because the dye outlet was at about the same level as the pump outlet, mixing was assumed to be instantaneous. The action of the pump appeared to mix the water and dye in the borehole thoroughly. Water was sampled from the borehole at 30-sec to 5-min intervals over the next 10 to 30 minutes. Each sample was discharged into one 40-mL glass vial and stored on site.

The samples were returned to the lab, covered and stored overnight (or longer) at room temperature. Standards were likewise maintained at room temperature. Samples were analyzed using a Turner Model 10 field fluorometer (Turner Designs 1981). A standard curve was developed for each day of measurement using standard solutions containing 10, 20, 50, 100, and 500 parts per trillion (ppt), 1, 5, 10, and 100 parts per billion (ppb), and 1 part per million (ppm) of Rhodamine WT. Standard solutions were prepared by the method of Wilson et al. (1986). The zero reading of the fluorometer was set using the 10-ppt standard solution, while the full scale reading was set by the 1 ppm standard solution. A standard solution within the sample range was read occasionally during analysis to check for instrument drift.

Each sample was poured into a cuvette for analysis. After measuring the Rhodamine level, the cuvette was emptied and rinsed twice with distilled water before refilling with the next sample. Sample vials and caps were rinsed with tap water, followed by distilled water, and then oven dried after completion of the test analyses.



a. Experimental setup. *b. Sub-ice dye injection system.*

Figure 2. Borehole dilution test equipment.

RESULTS

A total of 17 borehole dilution tests were conducted in eight boreholes. The logs of boreholes in the test area are shown in Figure 3. The borehole logs, while providing only a general or relative variation in the character of the frazil deposit, do indicate the stratified nature of the deposits in the study area. This interpretation is consistent with previous investigations at this location (Lawson et al. 1986a,b; Lawson and Brockett 1990, in prep.). These more detailed analyses of the frazil deposit's internal structure revealed a complex stratigraphy, with individual layers ranging from as little as 1 cm to over 1.5 m in thickness and extending laterally for several meters to over 100 m. During those studies, it became clear that downhole resistance reflected packing density and grain size distribution, and thus our logs actually may reflect both properties. The logs indicate that the deposit's properties are variable over relatively short distances and, further, that apparent inconsistencies or variabilities in the test data are probable.

Using the method described in Lewis et al. (1966), we developed a plot of the logarithm of the ratio of concentration at time t to maximum concentration vs time for each borehole dilution test (see App. A). Regression analyses were performed on the linear portion of each plot (Fig. 4). As is the practice in the analysis of borehole dilution test results in soils, data points for devel-

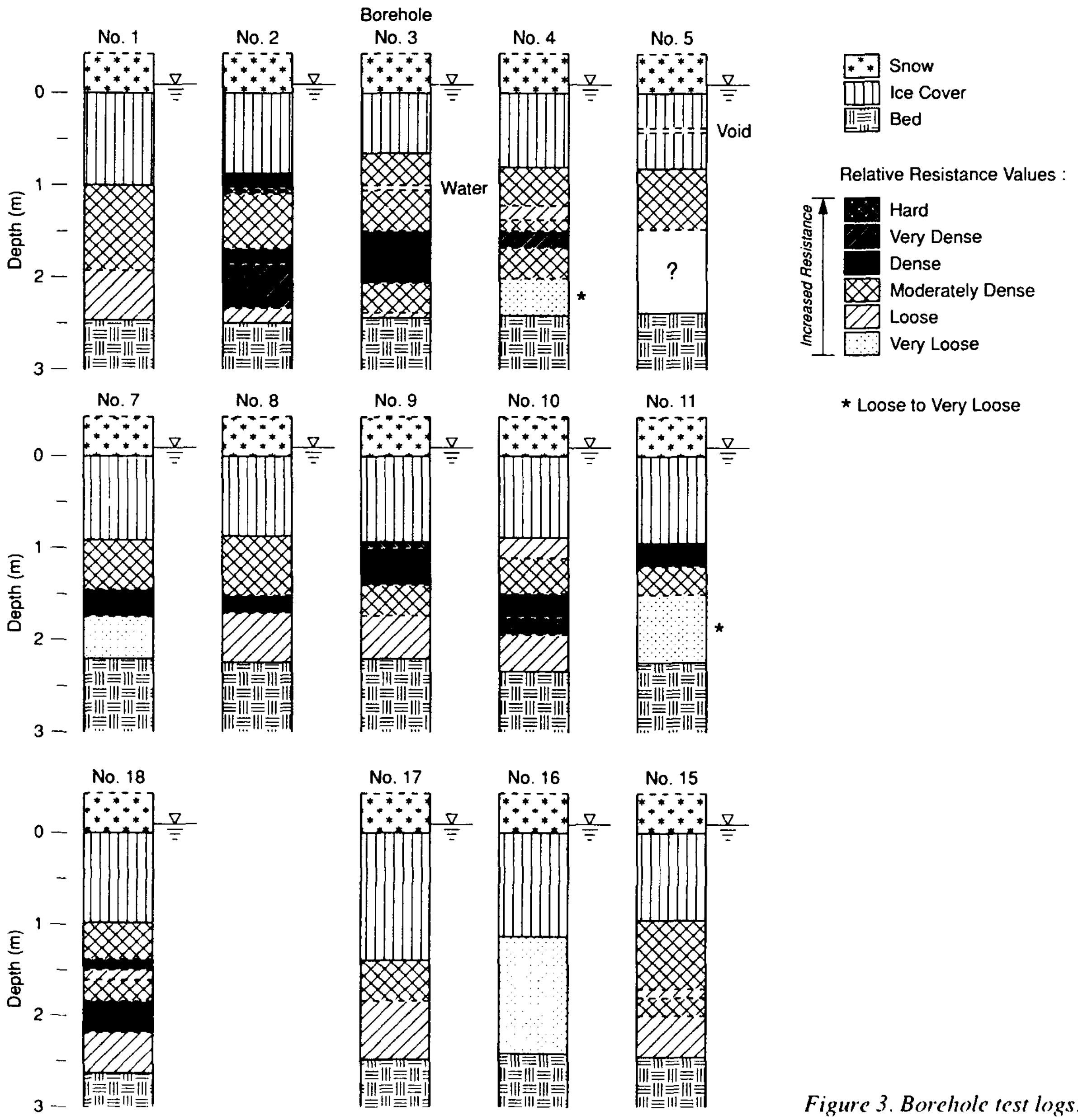


Figure 3. Borehole test logs.

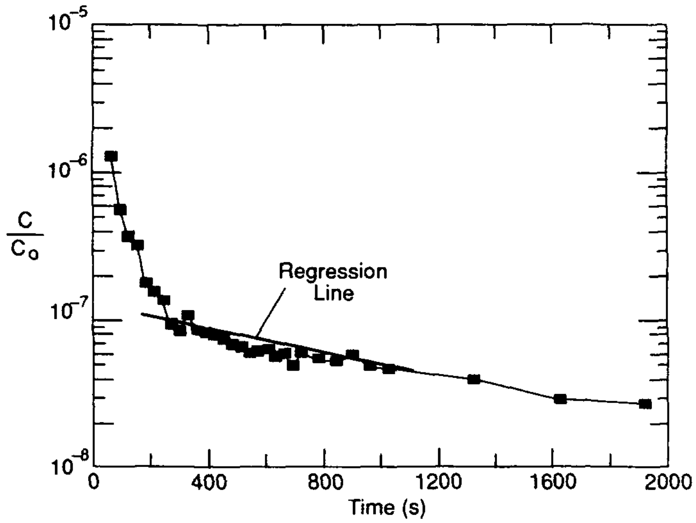


Figure 4. Example showing choice of regression line (borehole number 8, zone 1).

oping the slope ($-8v/\pi d$) were chosen by eye. Data from the initial period of rapid dilution, attributable primarily to diffusion, were excluded. Seepage velocity through the frazil ice deposit was calculated from eq 4, where C_0 was taken to be the highest level of fluorescence measured in each test.

Results of the tests are given in Table 1. The reported effective depth of each test is the thickness of the frazil ice in the borehole (i.e., the depth of the test less the solid ice thickness). Of the 17 tests, three did not yield slopes suitable for calculating seepage velocity. At the top of borehole 2, the dye injection device failed to work properly, and in the same hole at depth, the pump intake clogged with frazil ice immediately after starting the test. An intake screen was then added, eliminating clogging problems. In the lower layer of borehole 5 (5-2), the dye disappeared immediately, perhaps because the bottom of the borehole was very close to the base of the frazil deposit, or because of the presence of a conduit that rapidly diluted the dye. A conduit was suggested by a void logged at 42.5 to 46 cm below the surface of the ice cover.

In cases where borehole dilution tests were done at two different depths in the same borehole, the first test was performed in a borehole augered to the first test depth . The borehole was then deepened by the same method to the depth of the second test . In these cases, the seepage velocity of the second test (e.g., test 18-2 in borehole 18) represents an integrated velocity of flow for the entire borehole thickness, excluding the solid ice cover at the top of each borehole where flow was assumed to be negligible. Because differences in veloc-

Table 1. Borehole dilution test results.

Test no.	*Depth of test (cm)*	*Depth to solid ice (cm)*	*Depth to bed (cm)*	*Total depth of borehole (cm)*	*Effective depth (cm)*	*No. of points in slope*	*Slope (10^{-3})*	*Seepage velocity (10^{-3} cm/s)*
3–1	120	62	242	175*	58	13	–2.05	4.61
3–2	175	62	242	175*	113	20	–0.93	2.09†
4–1	150	84	243	150*	67	11	–1.76	3.95
5–1	124	89**	240	124	40	9	–2.57	5.78
8–1	150	86	225	200	64	22	–0.52	1.16
8–2	200	86	225	200	114	17	–0.44	1.00†
9–1	137	94	221	200	43	19	–0.29	0.66
9–2	200	94	221	200	106	9	–1.70	3.82†
10–1	150	89	235	175	61	13	–0.68	1.52
10–2	175	89	235	175	86	14	–0.52	1.17†
15–1	135	92.5	246	173	42.5	23	–0.52	1.17
15–2	173	92.5	246	173	80.5	22	–0.45	1.01†
18–1	140	98	235	180	42	15	–0.78	1.76
18–2	180	98	235	180	82	8	–0.75	1.68†

* May have penetrated to bed.
† Composite seepage velocity.
** Void from 42.5 to 46 cm.

Table 2. Comparison of composite vs zonal seepage velocities.

Test	Seepage velocity (10^{-3} cm/s) Composite	Upper test zone	Lower test zone
3–2	2.09	4.61	–0.58
8–2	1.00	1.16	0.79
9–2	3.82	0.66	5.98
10–2	1.17	1.52	0.29
15–2	1.01	1.17	0.83
18–2	1.68	1.76	1.60

ity between the upper and lower tests may represent differences in the internal properties of the deposit, the composite velocity of the entire borehole must be separated into its component parts:

$$v_c = \frac{v_1 D_1 + v_2 D_2}{D_1 + D_2} \tag{6}$$

where v_c is the composite velocity, v_1 is the velocity in the upper test zone of effective depth D_1, and v_2 is the velocity in the lower test zone to depth D_2, which equals the total effective depth less depth D_1. The calculated velocities for the lower zones are compared to those of the upper borehole tests in Table 2. The results show that while the lower part of boreholes 3, 8, 10, 15 and 18 had slower seepage velocities than the upper part, borehole 9 exhibited a higher seepage velocity at depth. The large difference between the velocity calculated for the upper layer of borehole 3 and the composite velocity for the same borehole is a result of the increased density of the frazil in the lower layer. Because of this large difference, the calculated velocity for the lower layer appears as a negative number. The negative sign thus indicates a very low velocity for the lower layer compared to that of the upper layer, but this is not a usable quantitative value. The high seepage velocity for borehole 5 and for the upper layer of borehole 3 reflect the presence of a void (see Fig. 3) in the frazil deposit. Similarly, the high seepage velocity of borehole 4 and the lower portion of borehole 19 are due to the loosely packed layers that these boreholes intersect.

Variations in intrinsic permeability with depth may correlate with variations in deposit properties associated with stratification, and thus should provide a method to independently identify different layers within frazil deposits. If we consider the integrative nature of our current test procedure, the seepage velocity measurements correlate reasonably well from hole to hole with resistance variations and thus the layered structure of the deposit (Fig. 3). These results were in part unexpected because of the complex stratigraphy that characterizes the frazil deposits here (Lawson and Brockett in prep.). The resistance logs indicate a complex layering, and a larger number of tests isolated within a limited depth range should be performed in each borehole for the test results to more accurately detail this internal structure. Since hole-to-hole variations of intrinsic permeability in the direction of flow (NNW) are basically inconsistent, we do not have knowledge of the stratigraphic relationships between the layers in each hole, and thus neither the precise flow paths nor the source of the seepage variations can be defined.

The average seepage velocity calculated from the seepage velocity of boreholes 4 and 5, as well as the composite seepage velocity for boreholes 3, 8, 9, 10, 15 and 18, is 2.56×10^{-3} cm/s. The Reynolds number based upon this velocity is less than 0.1, assuming a mean ice particle diameter of 2 mm and a kinematic viscosity equal to 1.787×10^{-2} cm^2/s (Batchelor 1967). Thus, the laminar flow condition required by Darcy's law is assumed valid. Water surface slopes measured by surveying represent very small changes in head within the deposit, also indicating that a groundwater flow analogy is appropriate.

Darcy's equation (eq 2) was therefore used to calculate intrinsic permeability using a mean water slope, dh/dl, of 0.00017. The dynamic viscosity was assumed to be 1.787×10^{-2} g/cm s and the fluid density 0.9999 g/cm^3 (Batchelor 1967). Hydraulic conductivity was then calculated using eq 1. The results (Table 3) fall within the range of values for a gravel deposit (Freeze and Cherry 1979, Todd 1980). Calculated values of intrinsic permeability and hydraulic conductivity for each borehole are given in Table 4.

The calculated values of intrinsic permeability (Table 3) are generally comparable to our borehole resistance logs (Fig. 3). Smaller calculated values occur within zones of mostly higher resistance (or density), whereas larger values tend to be associated with loose

Table 3. Frazil ice deposit properties calculated for each test.

Test no.	Seepage velocity (10^{-3} cm/s)	Intrinsic permeability (10^{-5} cm^2)	Hydraulic conductivity (cm/s)
3–1	4.61	49.4	27.1
3–2	–0.58	—	—
4–1	3.95	52.3	23.2
5–1	5.78	62.0	34.0
8–1	1.16	12.4	6.8
8–2	0.79	8.5	4.7
9–1	0.66	7.1	3.9
9–2	5.98	64.1	35.2
10–1	1.52	16.3	8.9
10–2	0.29	3.1	1.7
15–1	1.17	12.5	6.9
15–2	0.83	8.9	4.9
18–1	1.76	18.8	10.3
18–2	1.60	17.1	9.4

Table 4. Average frazil deposit properties estimated for each borehole.

Borehole no.	*Intrinsic permeability (10^{-4} cm^2)*	*Hydraulic conductivity (cm/s)*
3*	2.29	12.3
4	4.29	23.2
5	6.20	39.0
8*	1.07	5.9
9*	4.10	22.5
10*	1.25	6.9
15*	1.08	5.9
18*	1.80	9.9
Mean	2.75	15.1
Std deviation	1.76	9.7
COV	69%	69%

* Estimated from composite seepage velocity.

zones or zones containing one or more loose horizons within otherwise dense deposits. Given the nature of our logging and the integrated nature of the dilution test procedure, further direct comparisons are not possible using these data.

The intrinsic permeability of the frazil deposit may be used to estimate its porosity from the Kozeny-Carman equation (Todd 1980):

$$k = \frac{n^3 d_m^2}{180(1-n)^2} \tag{7}$$

in which n is porosity and d_m is a representative grain size, often taken as d_{10} in soils. Because the intrinsic permeability is a highly variable parameter, only a rough estimate of porosity is obtained. Using a frazil particle diameter of 2 mm as the representative grain size d_{10} and the calculated mean value of the intrinsic permeability (Table 4), the average porosity of the deposits calculated by eq 7 is 59.1%.

DISCUSSION

Data

Seepage velocities measured with the borehole dilution method are comparable to values measured in situ at this site in 1988 with a borehole thermal velocity meter (K-V Associates 1983; Lawson and Brockett, in prep.). This unit is a submersible probe, suspended at various depths within the deposit, which consists of four paired and opposing thermistors surrounding a central heat source. A heat pulse is generated and the thermal response of the thermistors is monitored. Thermal differences at the thermistors over a specified period of time measure the changes in a radial, transient temperature field caused by advection of heat due to the horizontal seepage velocity at each depth. Flow direction vectors in the horizontal plane are calculated from the differences in opposing thermistors, thus providing both a direction and magnitude for the seepage velocity. Flow rates ranging from 3.5×10^{-5} to 3.5×10^{-2} cm/s can be measured with the thermal velocity meter (K-V Associates 1983).

For the frazil deposit investigations, 7-cm-diam. boreholes were cut through the ice cover and the probe inserted progressively at 15- to 30-cm intervals to the bottom of the deposit. Descriptive logs were prepared from freeze-probe samples adjacent to each test hole. For 40 borehole tests, seepage velocities typically ranged from 1.4×10^{-3} to 5.0×10^{-3} cm/s, with considerable vertical variability in each borehole. Average seepage velocity was about 3.5×10^{-3} cm/s. Comparisons of these data to the descriptive logs showed good correspondence between changes in seepage velocity and layering within the deposit.

In comparison, seepage velocities calculated from borehole dilution data ranged from 0.29 to 5.98×10^{-3} cm/s, with a mean of 2.56×10^{-3} cm/s. Seepage velocities measured by borehole dilution are generally lower than the groundwater probe results, but this may be due to a variety of factors, including differences in frazil deposit structure, permeability, and grain size distribution at the time of testing. Dilution seepage velocities also show less variability than the groundwater probe data; we suspect this difference is due largely to the integrating nature of the borehole test over frazil thicknesses of approximately 0.4 m, whereas the probe data represent flow at a particular location. No direct comparisons of the two methods have been made, however.

Assuming the same slope and dynamic viscosity as used in calculating intrinsic permeability from the borehole tests, we calculated an average intrinsic permeability for the average probe seepage velocity of 3.5×10^{-3} cm/s as 3.76×10^{-4} cm^2, with a range of 1.5×10^{-4} cm^2 to 5.4×10^{-4} cm^2, similar to the range of values calculated from the borehole dilution tests.

Seepage velocities measured with the borehole dilution test in the field are about half of those obtained in laboratory experiments (White 1991). The borehole dilution test in natural frazil deposits also yields a longer period for measurement of changes in dye concentration and a more uniform dye concentration than observed in the tests in laboratory frazil deposits. The higher coefficient of variation (69%) for the field tests, while high, is still lower than the range reported by Nielsen et al. (1973). The coefficient of variation in the field tests reflects the complex stratigraphy of the frazil deposit compared to the more uniform laboratory deposits.

While the seepage velocities calculated from the laboratory and field tests are similar, it is difficult to compare the values of intrinsic permeability because of the disparity in test conditions. The laboratory test involved a large change in head over a short distance, and the Dupuit-Forchheimer discharge formula (Bear 1979) was used to calculate an average intrinsic permeability of 6.06×10^{-7} cm^2, several orders of magnitude smaller than found in the field. The average porosity calculated for the laboratory tests was 43.690, indicating that the order of the intrinsic permeability is reasonable for the laboratory conditions.

The constant head permeameter test results reported by Dean (1976) and Beltaos and Dean (1981) are the only previous attempts to determine the intrinsic permeability of natural frazil deposits. Because frazil ice is removed, drained and partly refrozen prior to saturating the ice with motor oil, the samples are effectively remolded. The packing, grain shape, tortuosity, and porosity of the deposit are modified by this procedure. The test results therefore may not accurately represent the intrinsic permeability of frazil deposits. The remolded samples will also tend to have similar grain orientations, packing and porosity, which in turn will result in test values for the intrinsic permeability that show little variation. This fact is borne out by the results of their five tests which vary by only 0.13×10^{-5} cm^2 between their maximum and minimum values. The difference between the permeameter and borehole dilution results may be attributed to the differences between the methods and the possible large variations in the structure of the frazil deposits tested (Table 5).

Table 5. Comparison of intrinsic permeability.

	Borehole dilution k (*cm²*)	*Dean (1976)* k* (*cm²*)	*Beltaos and Dean (1981)* k† (*cm²*)
Average value**	27.5×10^{-5}	1.53×10^{-5}	1.56×10^{-5}
Minimum	3.1×10^{-5}	—	1.50×10^{-5}
Maximum	64.1×10^{-5}	—	1.63×10^{-5}
Std. dev.	1.76×10^{-5}	—	9.19×10^{-7}

* Two tests.
† Three tests.
** See Table 4.

The porosity of the deposit can be estimated from the intrinsic permeability using the Kozeny-Carmen equation (eq 7) if data exist on the deposit's grain size variability. The range in ice particle sizes was determined for deposits at this location on the Tanana River in 1988 on ice sampled with the CRREL bulk sampler (Brockett and Sellmann 1986). Samples were sieved in the field and the grain-size distributions plotted. The results of these analyses indicated overall particle sizes ranging from < $^1/_2$-mm diameter to over 150 mm diameter, with typical sizes ranging from 1 mm to 25 mm in diameter (Lawson and Brockett in prep.). Mean grain sizes based upon these distributions ranged from about 2 to 8 mm.

Porosity values calculated from the average intrinsic permeability determined by the borehole dilution test for representative sizes d_{10} of 0.5 and 3.5 mm as previously defined by the bulk sample grain size distributions are 82.9% and 47.9%, respectively. For d_{10} of 2 mm, the average porosity was 59.1 %. These calculated values compare favorably with the range of porosities determined by direct measurement of ice and water volumes in bulk samples. The bulk porosities ranged from about 35% to 77%, with a mean of 52% for 15 samples. Each bulk porosity represents an average value for an integrated deposit thickness of about 1.4 m.

Test apparatus and procedure

Two aspects of the field test are difficult to control: dye injection and mixing. Ideally in this type of test, the dye would be instantaneously injected over the depth of the borehole and simultaneously mixed, since uniform concentration is assumed.

In the present procedures, dye was injected rapidly at a single point low in the borehole and the action of the pump was relied upon to provide adequate mixing. Dye concentration was assumed to be uniform by the time the first sample was taken, 30 seconds after dye injection. Nonuniform concentration early in the test should have a small effect on our results because the first few data points are discarded, but could have a greater effect later in the tests. Fortunately, the regularity of the data suggest that mixing was relatively uniform throughout the tests (see App. A). Simultaneous samples at different depths should be analyzed, however, to establish the quality of mixing provided by the pump.

In the future, variable-depth injection devices should be designed to determine the effect of the injection location on the data. A further refinement which we plan to develop is a method to test precisely delineated portions of the deposit at a given depth. This refinement could be accomplished by use of a borehole packer above and below the dye injection point, thereby limiting flow effects to the region between the packers. This type of test would require a greater knowledge of the effect of the borehole on flow. Such a method would permit detailed downhole measurements that could be related directly to the deposit stratigraphy at the borehole site.

CONCLUSIONS

The borehole dilution test appears to be applicable to in-situ field analyses of seepage velocities for calculation of the deposit's intrinsic permeability. Seepage velocities calculated by this method are comparable to those measured in situ with a groundwater flow meter.

Intrinsic permeability calculated from the seepage velocity data range from 3.1 $\times 10^{-5}$ to 64.1 $\times 10^{-5}$ cm^2, with an average value of 27.5 $\times 10^{-5}$ cm^2. Intrinsic permeabilities based upon permeameter tests on remolded samples, the only other known field analyses of this property, averaged 1.56 $\times 10^{-5}$ cm^2. Porosities calculated for the average intrinsic permeability of the deposit using previously measured d_{10} particle values compared well to porosities calculated from ice and water volumes in bulk samples.

Although there appears to be some relationship between the perceived resistance of the deposit to probing (which presumably is related to grain packing or grain-size variations) and seepage velocity, further detailed analyses are required to determine if the borehole dilution test can be used to indirectly infer the internal structure of frazil deposits.

Further refinement of this method is anticipated. Different dye injection and mixing methods are being examined because of potential difficulties with dye mixing in the borehole. In addition, a system using borehole packers is planned to permit discrete analyses of short, vertical segments within a borehole.

LITERATURE CITED

Batchelor, G.K. (1967) *An Introduction to Fluid Dynamics.* Cambridge, England: Cambridge University Press.

Bear, J. (1979) *Hydraulics of Groundwater.* New York: McGraw-Hill Book Company.

Beltaos, S. and A.M. Dean, Jr. (1981) Field investigations of a hanging dam. In *Proceedings, IAHR Symposium on Ice, 27–31 July 1981, Quebec, Canada*, vol. 3 p. 475-85.

Brockett, B. and P. Sellmann (1986) Development of a frazil ice sampler. USA Cold Regions Research and Engineering Laboratory, Special Report 86-37.

Davis, S.N., G.M. Thompson, H.W. Bentley and G. Stiles (1980) Groundwater tracers—A short review. *Ground Water*, **18**(1): 14–23.

Dean, A.M., Jr. (1976) A method for determining the permeability of frazil ice. USA Cold Regions Research and Engineering Laboratory, Technical Note (unpublished).

Freeze, R. A. and J..A. Cherry (1979) *Groundwater.* Englewood Cliffs, New Jersey: Prentice-Hall.

Harr, M.E. (1987) *Reliability-Based Design in Civil Engineering.* New York: McGraw-Hill .

Hvorslev, M.J. (1951) Time lag and soil permeability in groundwater observations. USA Waterways Experiment Station, Vicksburg, Mississippi, Bulletin No. 36.

K-V Associates (1983) Groundwater flowmeter system. Operations and maintenance manual. Model 40, K-V Associates, Falmouth, Massachusetts.

Lawson, D.E., E.F. Chacho, Jr., B.E. Brockett, J.L. Wuebben, C.M. Collins, S.A. Arcone and A.J. Delaney (1986a) Morphology, hydraulics and sediment transport of an ice-covered river: Field techniques and initial data. USA Cold Regions Research and Engineering Laboratory, CRREL Report 86-11.

Lawson, D.E., E.F. Chacho, Jr. and B.E. Brockett (1986b) Subice channels and longitudinal frazil bars, ice-covered Tanana River, Alaska. In *Proceedings of 8th IAHR Symposium on Ice, 18-22 August 1986, Iowa City, Iowa.* vol. 1 p. 465–474.

Lawson, D.E. and B.E. Brockett (1990) In-situ sampling and characterization of frazil ice deposits. *Cold Regions Science and Technology*, **17**: 193–205.

Lawson, D.E. and B.E. Brockett (In prep.) Structure and stratigraphy of frazil deposits. In preparation.

Lewis, D.C., G.J. Kriz and R.H. Burgy (1966) Tracer dilution sampling techniques to determine hydraulic conductivity of fractured rock. *Water Resources Research*, **2**(3): 533-542.

Nielsen, D.R., J.W. Biggar and K.T. Erh (1973) Spatial variability of field-measured soil-water properties. *Hilgardia, Journal of Agricultural Science* (California Agricultural Experiment Station), **42**: 215–260.

Todd, D.K. (1980) *Groundwater Hydrology.* New York: John Wiley and Sons, Inc.

Turner Designs (1981) Operating and service manual: Model 10 Series Fluorometers. Turner Designs, Mountain View, California.

White, K.D. (1991) Determining the intrinsic permeability of frazil ice. Part 1: Laboratory investigations, USA Cold Regions Research and Engineering Laboratory, CRREL Report 91-23.

Wilson, J.F., Jr., E.D. Cobb and FA Kilpatrick (1986) Fluorometric procedures for dye tracing. U.S. Geological Survey, TWRI Book 3, Chapter A12.

APPENDIX A: DILUTION CURVES

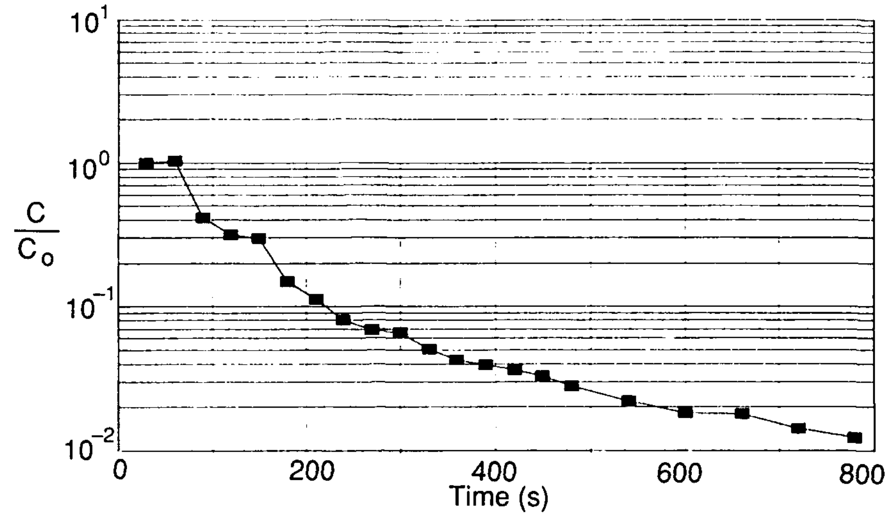


Figure A1. Hole 3, test 1, 6 April 1991.

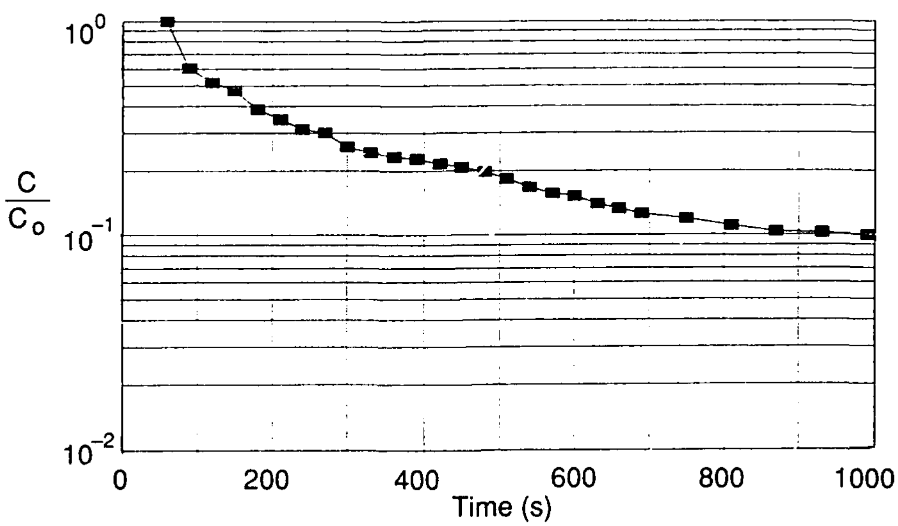


Figure A2. Hole 3, test 2, 6 April 1991.

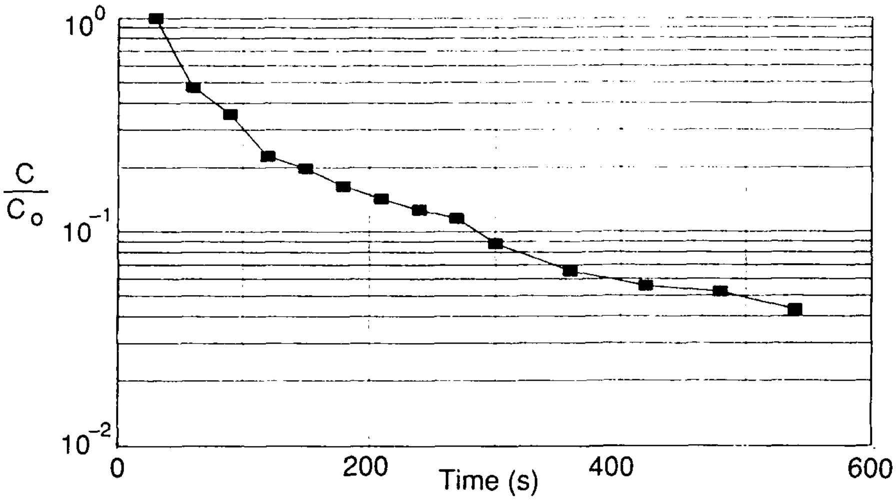


Figure A3. Hole 4, test 1, 6 April 1991.

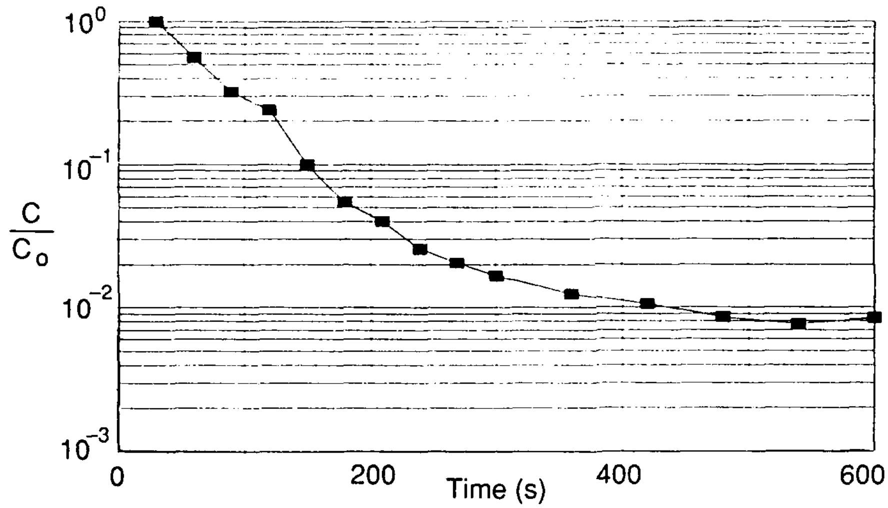


Figure A4. Hole 5, test 1, 6 April 1991.

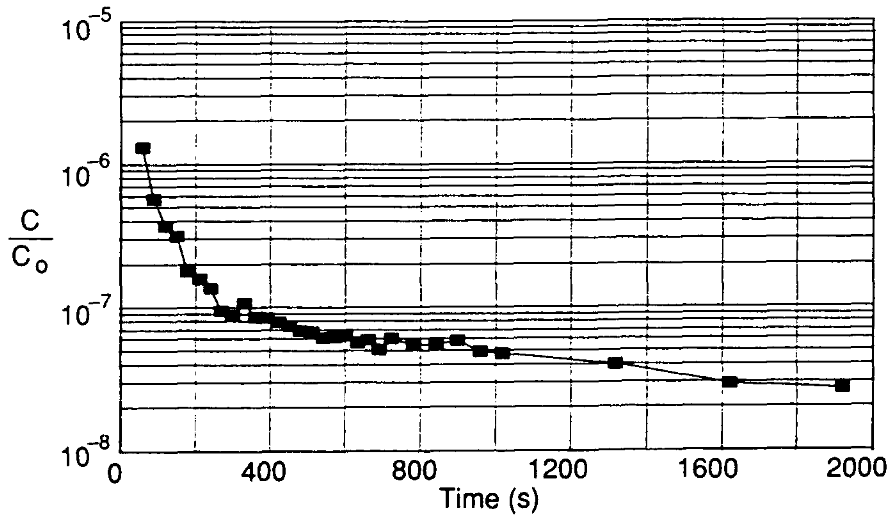


Figure A5. Hole 8, test 1, 7 April 1991.

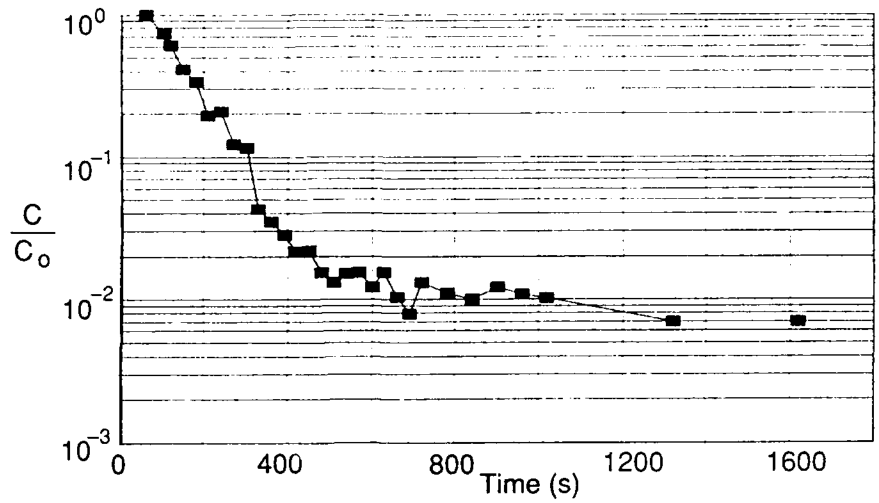


Figure A6. Hole 8, test 2, 7 April 1991.

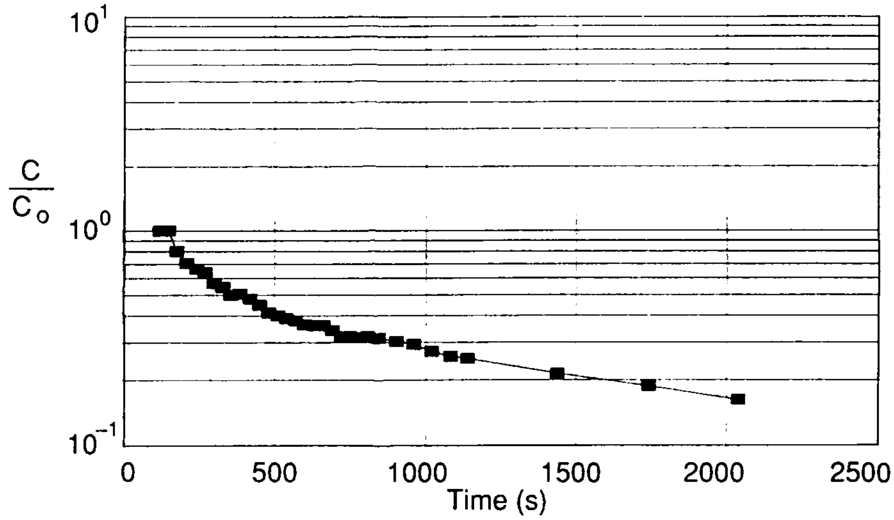


Figure A7. Hole 9, test 1, 7 April 1991.

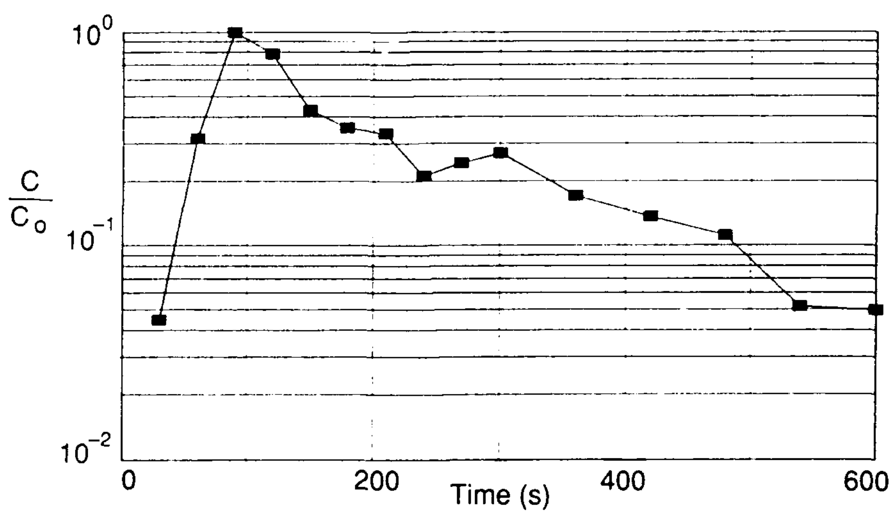


Figure A8. Hole 9, test 2, 7 April 1991.

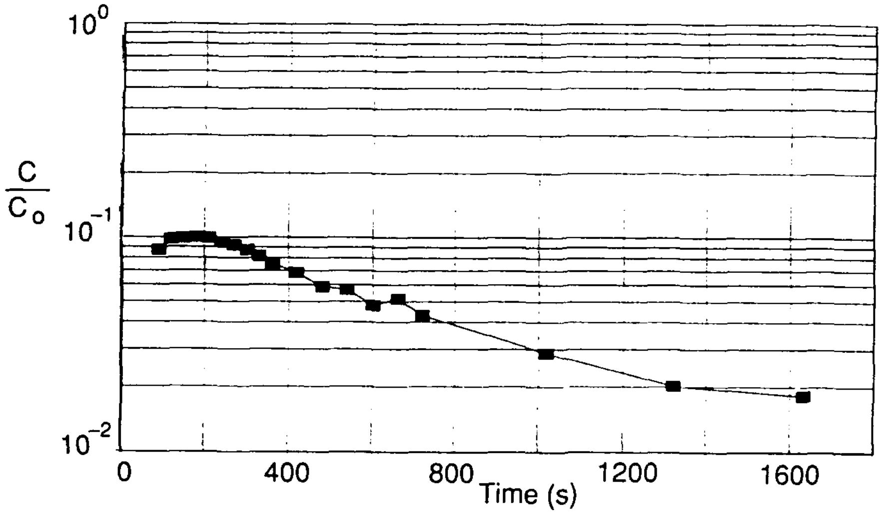


Figure A9. Hole 10, test 1, 7 April 1991.

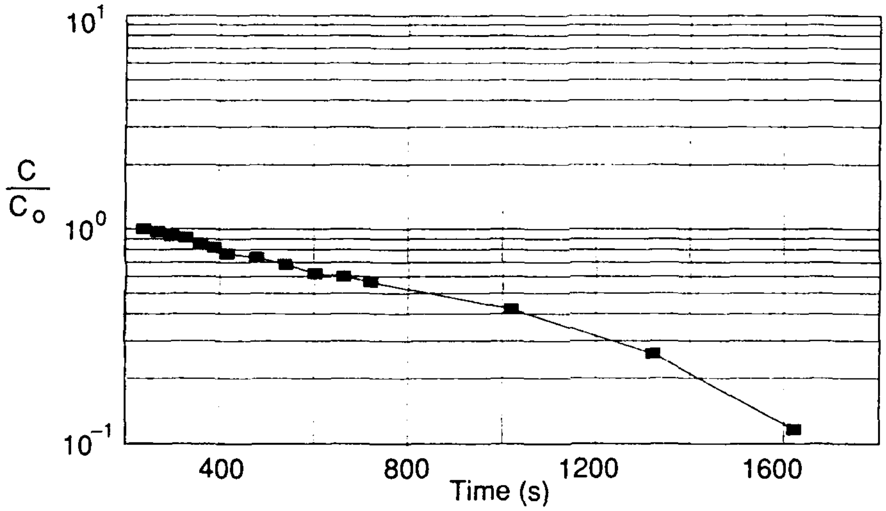


Figure A10. Hole 10, test 2, 7 April 1991.

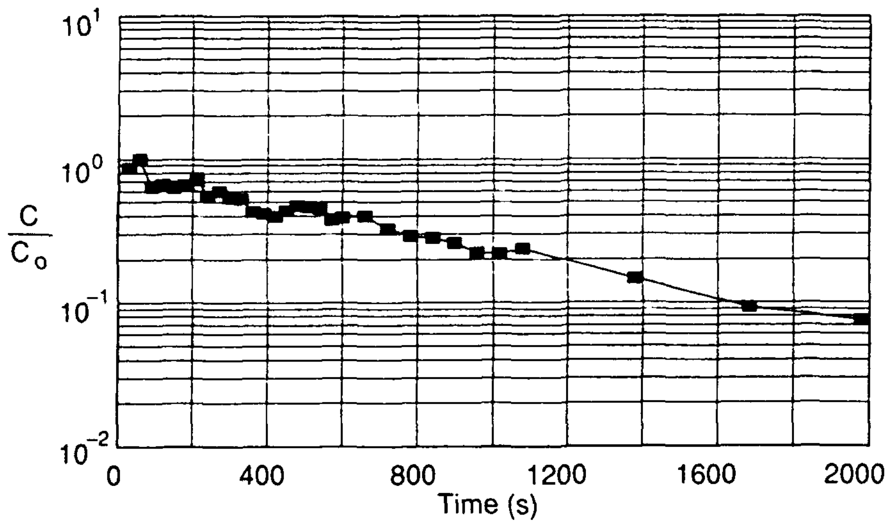


Figure A11. Hole 15, test 1, 8 April 1991.

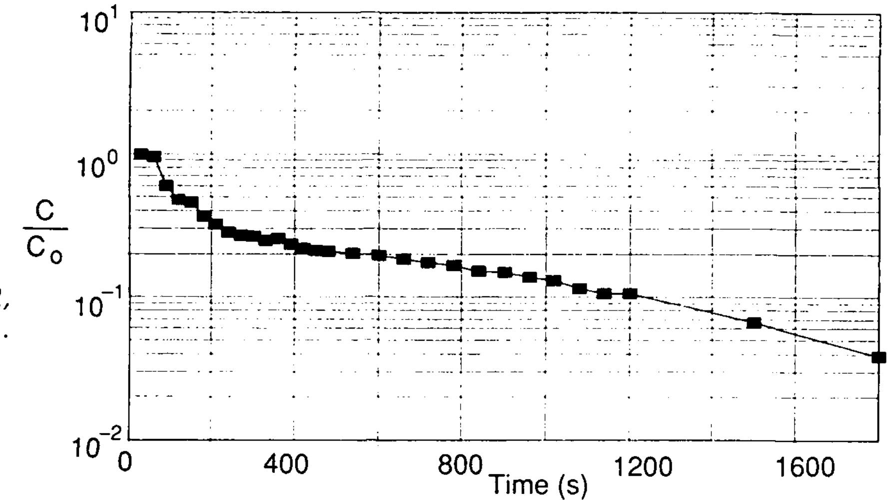


Figure A12. Hole 10, test 2, 8 April 1991.

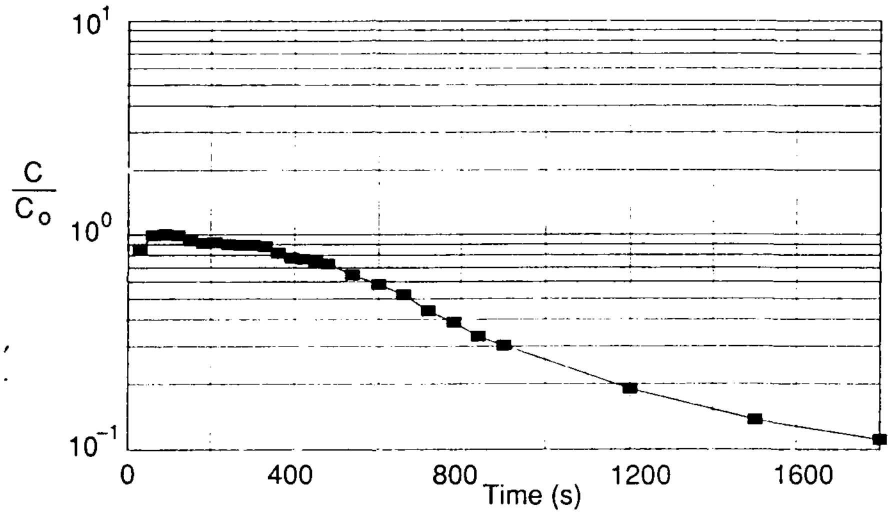


Figure A13. Hole 18, test 1, 8 April 1991.

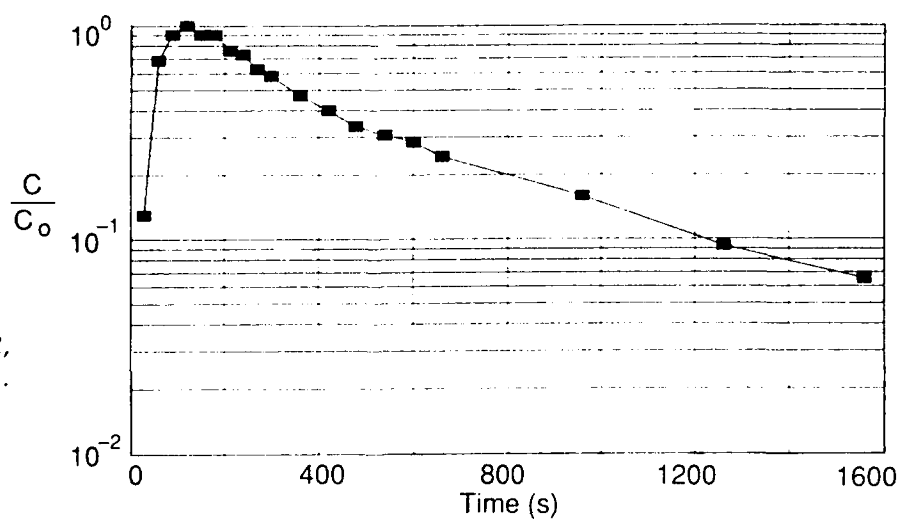


Figure A14. Hole 18, test 2, 8April 1991.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1992	

4. TITLE AND SUBTITLE

Determining the Intrinsic Permeability of Frazil Ice
Part 2: Field Investigations

5. FUNDING NUMBERS

6. AUTHORS

Kathleen D. White and Daniel E. Lawson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

CRREL Report 92-7

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The intrinsic permeability of a frazil deposit can be used to describe its flow capacity and structure. Because of the nature of frazil ice, an in-situ test is desirable when determining this parameter in natural frazil deposits. This report describes the application of the borehole dilution test to determine seepage velocity, which is then used to calculate intrinsic permeability and estimate porosity. Seepage velocities ranged fron 0.29×10^{-3} to 5.98×10^{-3} cm/s (2.56×10^{-3} cm/s average) , with an average intrinsic permeability of 2.75×10^{-4} cm^2. Porosities for d_{10} grain sizes of 0.5 and 3.5 were 82.9 and 47.5 %, respectively. Seepage velocity and porosity data are also compared to laboratory data from borehole dilution tests, data measured previously at the same location with an in-situ groundwater flow meter, and to permeameter test results on remolded samples.

14. SUBJECT TERMS			15. NUMBER OF PAGES
Borehole	Frazil ice	Intrinsic permeability	23
Dilution	Hydraulic conductivity	Porous flow	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL