Field and laboratory acoustic testing of frozen soils

P.B. FRANSHAM
Hardy Associates (1978) Ltd., 221-18 Street S.E., Calgary, Alberta, Canada T2E 6J5

J.D. UNRAU
Department of Earth Science, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

AND

S.N. REESOR
Hardy Associates (1978) Ltd., 221-18 Street S.E., Calgary, Alberta, Canada T2E 6J5

Research was undertaken to investigate the compressional wave velocities in frozen soils. Samples were obtained during two consecutive field seasons from Illisarvik lake, N.W.T. Compressional wave velocities were measured on cores in the field using portable ultrasonic testing equipment. Velocity measurements were made at a single temperature and, hence, yielded a single point on a velocity *versus* temperature curve. Grain-size and moisture content tests serve as a base for intepreting wave velocities. Velocities obtained from field surveys show a strong correlation with those obtained from laboratory measurements. This suggests that one should be able to differentiate ice-rich from ice-poor zones, and, hence, obtain an impression of the spatial distribution of the ground ice.

Compressional wave velocities have also been measured on a series of kaolinite and sand mixtures. Kaolinite to silica sand mixtures were made in the following ratios; 1.0, .75, .50, .25, and 0. Water contents ranged from 3 to 45 per cent. The samples were compacted using the modified Proctor method. The results show a strong dependence of velocity on moisture content, the proportion of sand to clay, and the bulk density.

On a entrepris une étude des vitesses de propagation des ondes de compression dans des sols gelés. Des échantillons ont été recueillis pendant deux saisons consécutives de travaux sur le terrain au lac Illisarvik (T.N.-O.). Les vitesses de propagation des ondes de compression ont été mesurées dans des carottes sur le terrain à l'aide d'un appareil ultrasonique portable. Les mesures de la vitesse ont toutes été effectuées à une même température et se traduisent par conséquent par un seul point porté sur la courbe de la vitesse en fonction de la température. Des mesures de granulométrie et de la teneur en humidité servent de base à l'interprétation des vitesses de propagation des ondes. Les vitesses mesurées sur le terrain présentent une forte corrélation avec les mesures de la vitesse effectuées en laboratoire, ce qui suggère qu'il devrait être possible de différencier les zones riches en glace et les zones pauvres en glace et par conséquent d'obtenir une représentation de la répartition spatiale de la glace dans le sol.

Les vitesses de propagation des ondes de compression ont également été mesurées pour un ensemble de mélanges de kaolinite et de sable. Les mesures ont porté sur des mélanges de kaolinite et de sable quartzeux dans les proportions suivantes: 1,0, 0,75, 0,50, 0,25 et 0,0. Les teneurs en eau variaient de 3 à 45 pour cent. Les échantillons ont été compactés par la méthode de Proctor modifiée. Les résultats révèlent d'étroites relations entre la vitesse et la teneur en humidité, la proportion de sable dans l'argile et la densité apparente.

Proc. 4th Can. Permafrost Conf. (1982)

Introduction

Logistical difficulties and climatic uncertainty, limit the effectiveness of site investigations in northern regions. The success or failure of a project is highly dependent on the quality and quantity of site information that is available. Surface and borehole seismic surveys can provide substantial back-up data on the nature and distribution of ice, if sufficient calibration of the wave velocities is available. It has been documented that the seismic velocities are a function of the temperature, ice content, and mineral composition of the soil. To better understand this phenomenon and to interpret the growth of ice lenses at the Illisarvik drained lake experimental site, field and laboratory investigations of the compressional wave velocities of Illisarvik soils were carried out. Ultrasonic testing techniques were used to measure the compressional wave velocity and those values are compared to field measurements obtained by Hunter (*pers. comm.*).

In addition to the field testing, a series of laboratory experiments were carried out on compacted samples of kaolinite and sand. The purpose of these tests was to determine the relationships between the compressional wave velocity, clay content, moisture content, and bulk density. All of the tests were carried out over a temperature range from -9.0 to 0.0°C.

Background

A proposal to drain a northern lake and, hence, to study the growth of permafrost under natural conditions was proposed by J. Ross Mackay in 1973. A lake on Richard's Island in the Mackenzie Delta was

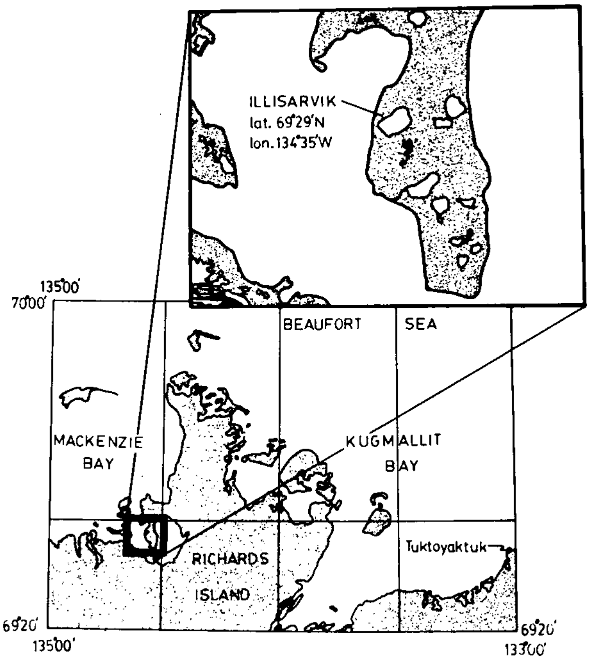

FIGURE 1. Location map for Illisarvik lake.

chosen and was subsequently drained during the summer of 1978 (Figure 1). The site has provided a natural field laboratory for multidisciplinary study of permafrost. Research on geophysical testing techniques, empirical observations of ice growth, and a study on the isotope concentrations in the frozen pore water are currently being carried out at Illisarvik.

Personnel from the Department of Earth Sciences, University of Waterloo, carried out a drilling program during May, 1979, and May, 1980 (Figure 2). Samples were obtained using a standard CRREL type barrel. The samples were logged in the field, and, during the latter field season, bulk density and velocity measurements were made on the cores within three to four hours of sampling. All samples were then shipped to the University for further testing. The survey grid was established by the GSC and all coordinate measurements are with respect to this grid. Fifteen boreholes were drilled during the 1979 field season, primarily for isotopic analyses. A further four holes were drilled during the 1980 season for velocity measurements. Results are presented here for one hole from the 1979 series (ILL-3), and for the four 1980 series holes (PBF-1 to 5, PBF-4 was abandoned). Since 1979, samples have been used primarily for isotope studies, that involved the squeezing out of the pore water. Velocity measurements were, therefore, made on samples that were reconstituted back to the original field moisture content. The generalized soil description bulk density, moisture content, and grain-size distribution for borehole 3 (co-ordinates 350N, 200E) are given (Figure 3). Judging from the high moisture contents, excess ice was present over the entire core. The sediments are primarily silt-sized, with sand and lesser amounts of clay-sized particles. Description of the 1980 soils is given in a subsequent section.

Sample Preparation

Illisarvik Samples

Samples were described in the field according to the standard National Research Council classification. Transportation limitations did not allow for samples to be shipped in the frozen state. Some moisture was lost during shipping, however, samples were reconstituted back to their field bulk density and moisture content. Reconstitution was accomplished by assuming a specific gravity for the soil grains of 2.65 and for ice of 0.917. Since the actual bulk density was measured in the field, it was possible to cal-

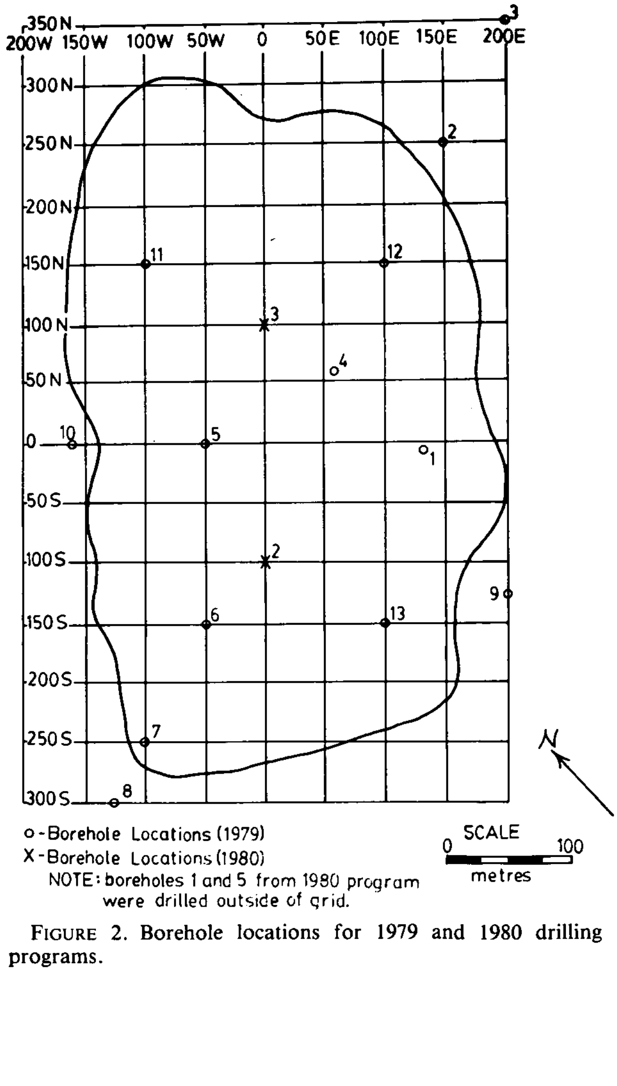

FIGURE 2. Borehole locations for 1979 and 1980 drilling programs.

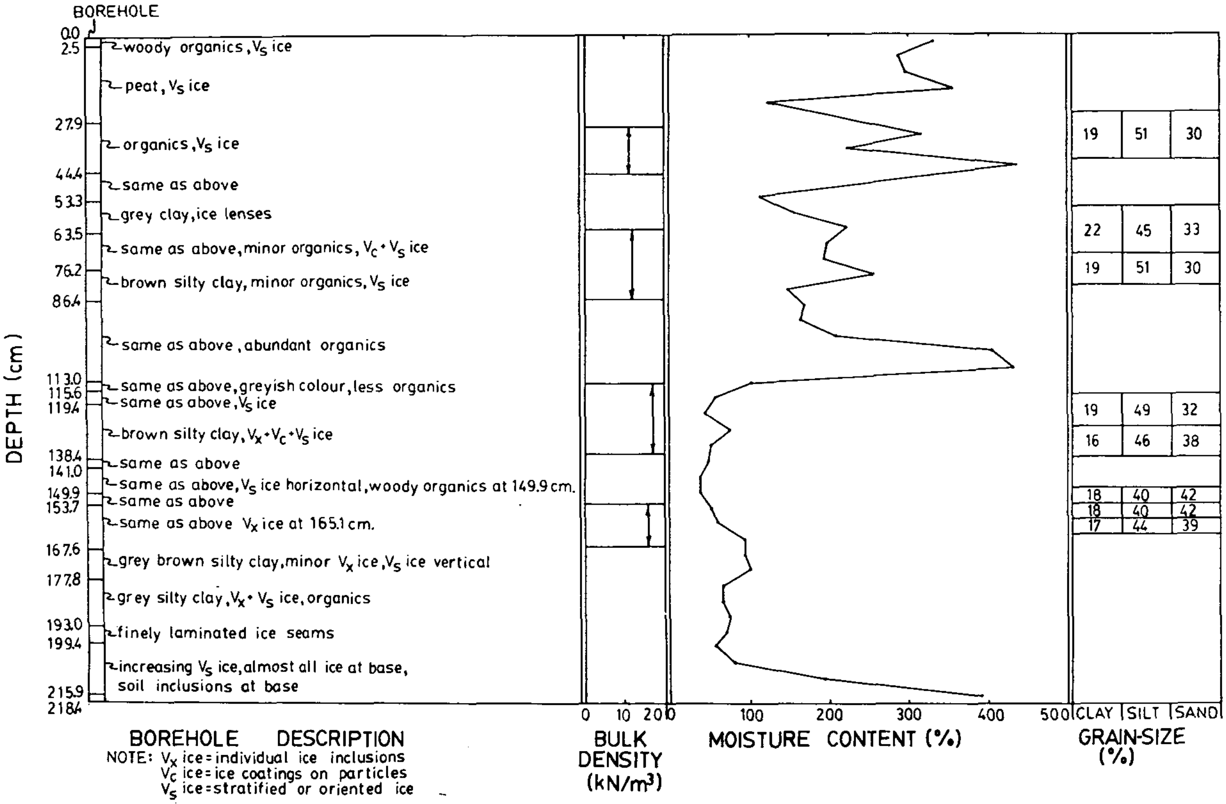

FIGURE 3. Borehole log for Hole III — 3, co-ordinates 350N, 200E.

culate a moisture content. For those samples that apparently did not lose any moisture, moisture contents were determined in the lab, as were grain-size distributions. Plexiglass cylinders were used as sample molds and, using a calculated volume of soil and moisture, the cylinders were filled to capacity prior to freezing.

Samples were then frozen according to a method described by Baker (1976). Samples were placed in a box and surrounded with vermiculite insulation on to the brim of the plexiglass cylinder. The box was then placed in the cold room and the frost front was allowed to penetrate in a vertical manner. In some of the preliminary tests a poor distribution of moisture was obtained. Therefore, the samples were periodically turned over and the soil was further mixed with the water. As the temperature approaches the freezing point and ice crystals begin to form, settling of the soil particles is partially inhibited by the ice crystals, and a more uniform soil–ice distribution is obtained. The temperature at the base of the cylinders was monitored and, once the samples reached the temperature of the cold room (– 13°C), the ends of the samples were ground flat and made parallel prior to testing. Since several samples were prepared at the same time, those that were not being tested immediately were sealed in plastic bags and returned to the vermiculite box until required.

Kaolinite–Sand Mixtures

In order to investigate the relationships between moisture content, bulk density, temperature, and compressional wave velocity, a series of sand–kaolinite mixtures were prepared. Five mixtures were prepared in the following porportions: 0 per cent sand, 25 per cent sand, 50 per cent sand, 75 per cent sand, and 100 per cent sand. In all, twenty-two samples were prepared, consisting of varying moisture content and percentage of sand. The samples were then compacted using a modified Proctor compaction method (ASTM Standard D1557). All samples except those of pure sand were prepared in this manner. The pure sand lacked sufficient cohesion to remain in a cylindrical shape and therefore these sand samples were prepared using the techniques described for the Illisarvik samples. However, since the moisture was evenly distributed, there was no need to invert the samples during the freezing process. Once the samples were frozen, the ends were ground flat and made parallel prior to testing.

Apparatus and Procedures

Laboratory Testing

Since the samples with high moisture contents tended to fail at temperatures close to freezing, it became necessary to incorporate a triaxial pressurizing system into the apparatus used for the laboratory testing program (Figure 4). In the initial stages, all testing was carried out under uniaxial loads.

Basically, the apparatus consists of an insulated chamber inside a cold room. The chamber is temperature controlled and allows for sample testing at varying temperatures. Ultrasonic compressional wave velocities were measured using a commercially available testing machine (PUNDIT). The PUNDIT generates a voltage pulse that is transformed into mechanical energy through piezoelectric crystals. A second transducer picks up the mechanical pulse and transforms the pulse back to a voltage. Auxiliary equipment allow for wave-form display on an oscilloscope and for the recording of the travel time through the sample on an X–Y recorder. The Y axis of the recorder measures the travel time, while the X axis records temperature. In this manner, it is possible to monitor the complete velocity temperature curve with a minimum amount of supervision by the operator. Upgrading of the equipment has included a second thermistor to measure the temperature at the centre of the sample as well as just below the upper transducer. This allows for much greater control of the temperature within the sample and provides a measure of the temperature variations within the samples. A linear voltage displacement transformer (LVDT) was used to measure the axial deformation as the sample was tested. Since it was no longer possible to monitor all of the functions on an X–Y plotter, a data-acquisition system was used to record all of the data. The data was subsequently transferred to the main computer for plotting.

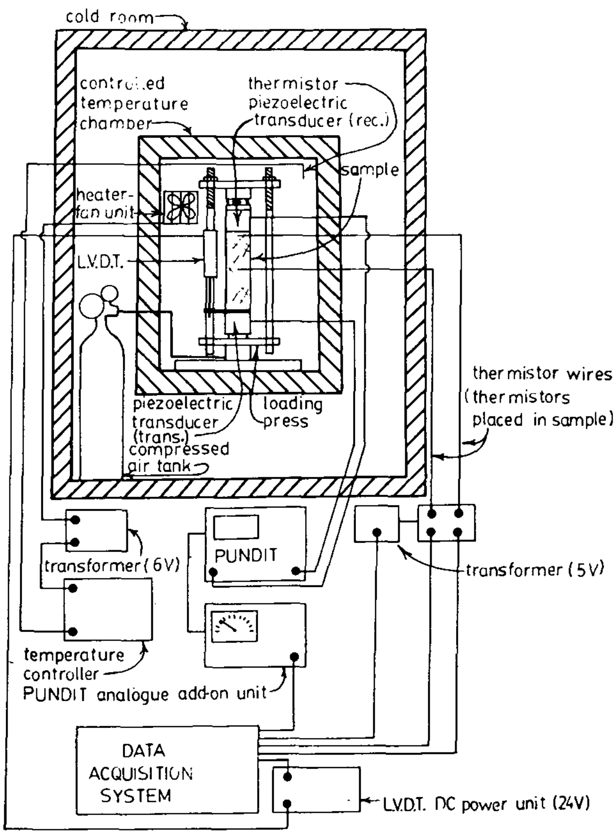

FIGURE 4. Laboratory equipment set-up.

Field Testing

Since the PUNDIT is portable, it was possible to measure the velocity of samples in the field. Since it was not feasible to test the cores immediately following drilling, the samples were stored for approximately three to four hours prior to testing.

The ambient air temperature averaged $-6°C$, and the samples likely had reached temperature equilibrium with the air temperature. All cores were trimmed to approximately 10 cm in length using a carpenter's saw, and heavy grease was applied to the ends of the sample, to provide acoustic coupling between the transducers and the sample. The transducers were then held manually against the ends of the sample and the travel time through the sample was recorded. Under ideal conditions in the laboratory, the PUNDIT is accurate to 0.1 μ/s or about 0.2 per cent. However, in the field, accuracy is estimated to be better than two per cent. Measurement errors are incurred due to irregularities in the timed sample ends and the force applied to the transducers. A jig to trim the sample ends flat and parallel and a portable field press would both facilitate the measurements and improve accuracy.

Laboratory Results

There is a distinct relationship between the water content and the density to which a sample can be compacted. Since clays have a stronger affinity for water than silt or sand particles, a high water content is usually required to compact a clay soil to its optimum density. The relationship between bulk density, velocity, and grain-size gradation is shown (Figure 5). The clay-rich soils compact to a lower density at the same water content as the sand-rich mixtures. A pure clay sample compacts to a bulk density of approximately 1.5 g/cc, while a 25 per cent clay sample can be compacted to approximately 2.2 g/cc. The increase in density results in increased grain-to-grain

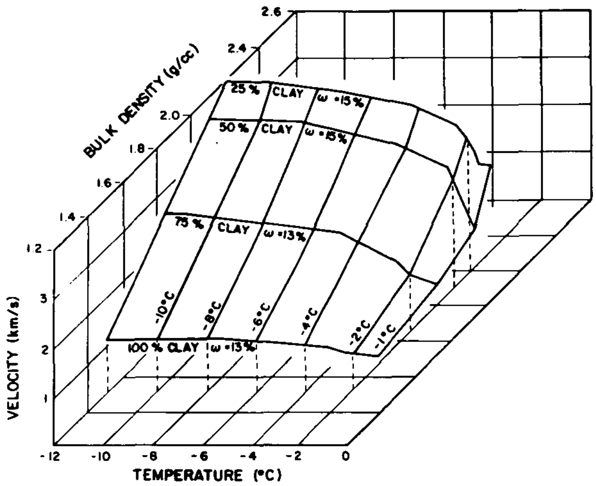

FIGURE 5. Variation in the compressional wave velocity with percentage clay and bulk density.

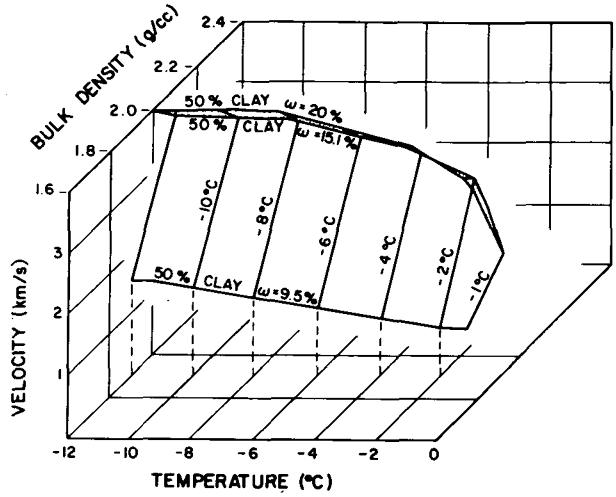

FIGURE 7. Variation of the compressional wave velocity for 50 per cent clay.

contact as illustrated by the linear increase in velocity from 1 to 4 km/s. The water content also contributes to the velocity (*see* Figure 5). With the denser, sand-rich mixtures, there is more grain-bonding, as illustrated by the greater decrease in the velocity upon thawing.

Moisture Content Effects

While it was shown in the previous section that the moisture content influences the density and, hence, the velocity, the effects of water content on velocity are shown more dramatically in Figures 6 and 7. Although the curves are not complete, in that excess ice is not present, they do show that, with an increase in moisture content, there is an increase in the velocity, up to a threshold value, after which the velocity does not increase significantly with increasing moisture content. This threshold value effect is better demonstrated in Figure 8, in which, velocity–temperature curves for reconstituted field samples have been incorporated. At moisture contents greater than 20 per cent, there is little or no increase in velocity with increasing moisture content. It is postulated that, at these higher moisture contents, grain-to-grain contact between the mineral components is lost, and the wave travels primarily through the interstitial ice. Therefore, it would appear that the compressional wave velocity should delineate ice-rich sediments from under-saturated, ice-poor materials. However, the percentage of excess ice may not be obtained from simple velocity measurements.

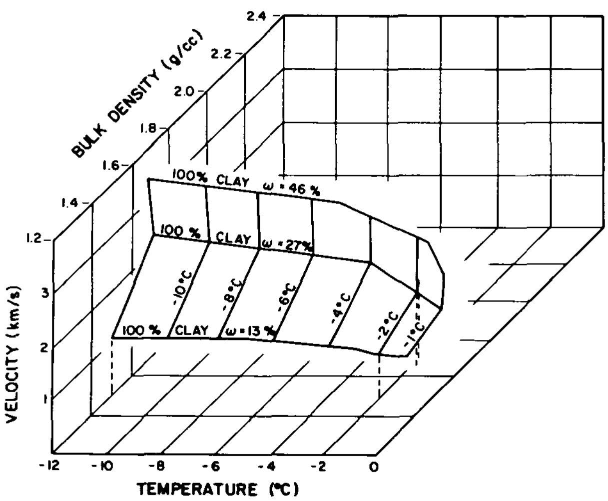

FIGURE 6. Variation of the compressional wave velocity for 100 per cent clay.

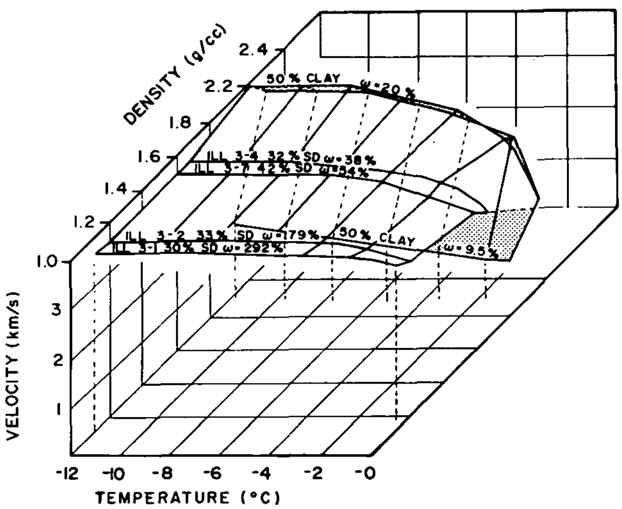

FIGURE 8. Composite plot of field samples and laboratory samples.

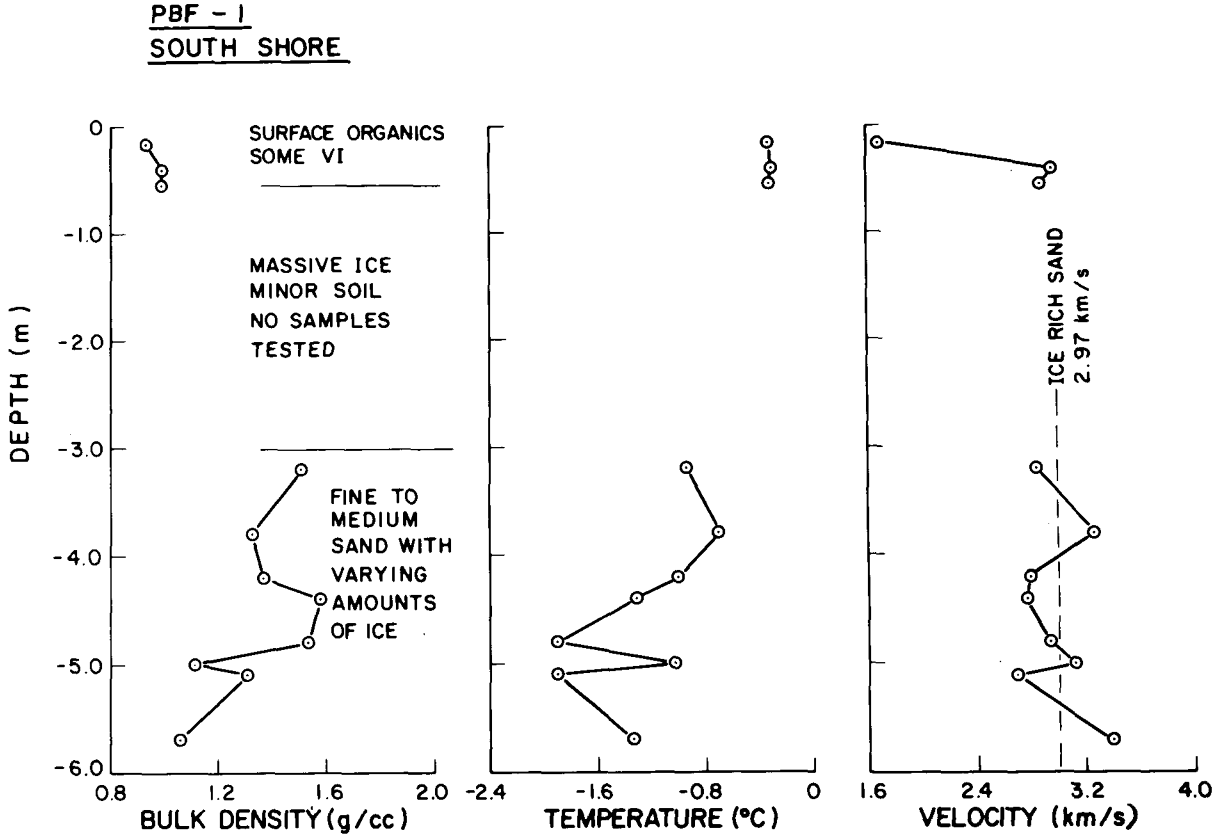

FIGURE 9. Borehole log for PBF-1.

Field Results

Four boreholes were drilled at the Illisarvik drained lake experimental station during the 1980 field season (Figures 9 to 12). The temperature data for each of the tests has been incorporated into the figures. However, there does not appear to be any relationship between the velocities and the temperatures. Temperatures were measured with a thermistor inserted into the centre of the sample. There is the possibility that moisture shorted out the thermistor, thereby giving the appearance of higher temperatures or, it is possible that the sample had not come to equilibrium following the drilling of the thermistor hole.

Borehole number 1 was drilled in the sediments forming the shores of the lake. A massive ice lens was identified at a depth of 0.5 to 3 m. From 3 to 5.75 m there was fine-to-medium sand with varying amounts of visible ice. The variation in the bulk density indicates the variation in the ice content. The average velocity for the soil is 2.97 km/s. The higher velocities are associated with the higher ice contents and the lower bulk densities.

Boreholes 2 and 3 were drilled in the organic sediments that form the lake bottom. Ice-bonded sediments were identified to a depth of 2.4 m. At depths greater than 2.4 m, the sediments were too soft to sample with the CRREL barrel. The freezing of the lake bottom has produced ice-rich sediments in the upper one metre. At depths between 1 and 2.4 m, the sediments are bonded, but there is little or no visible ice. The bulk densities are generally higher in borehole 3 than in borehole 2. As a result, the velocities are generally higher in borehole 2. The average velocity in ice-rich sediments is 3.17 km/s, while in ice-poor sediments, the average is 2.75 km/s. These values contrast with the average values from borehole 3 of 2.75 km/s and 2.54 km/s for ice-rich and ice-poor sediments, respectively. The curves for velocity *versus* depth and bulk density *versus* depth are approximately mirror images, and the higher the bulk density, the lower the velocity (*see* Figures 10 and 11).

Borehole 5 was drilled near the top of the ridge that forms the north shore of the lake. The stratigraphic profile, bulk density, temperature, and velocity data are shown (*see* Figure 12). Here again, there is a strong correlation between the velocity and the bulk density. The ice-poor sand has a velocity of 2.97 km/s, while the ice-rich sand has an average

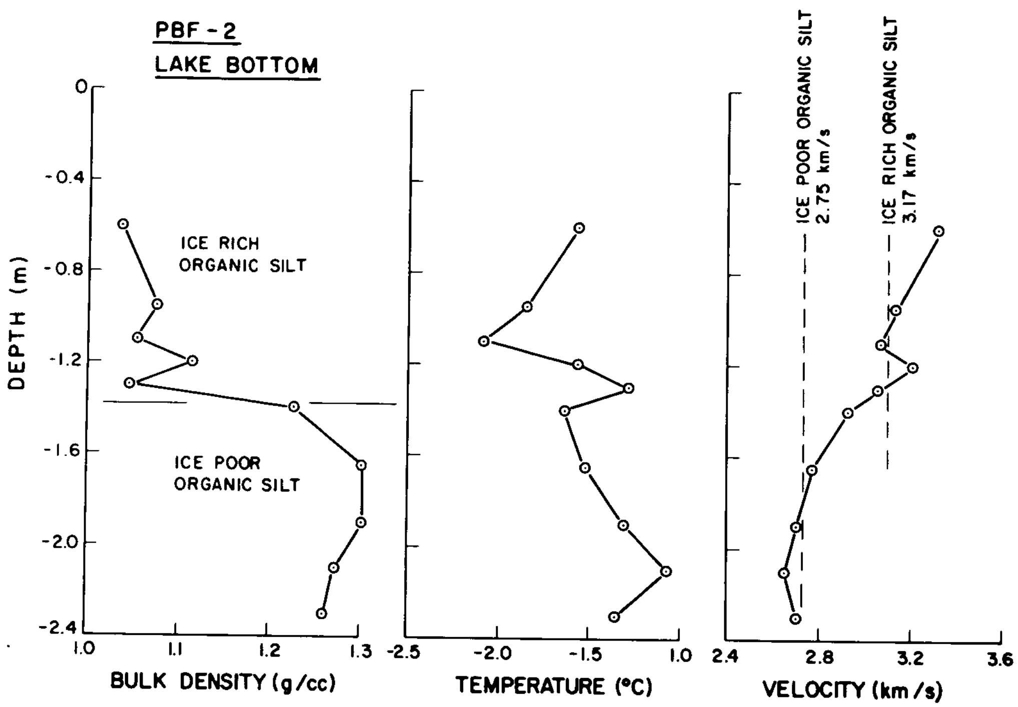

FIGURE 10. Borehole log for PBF-2.

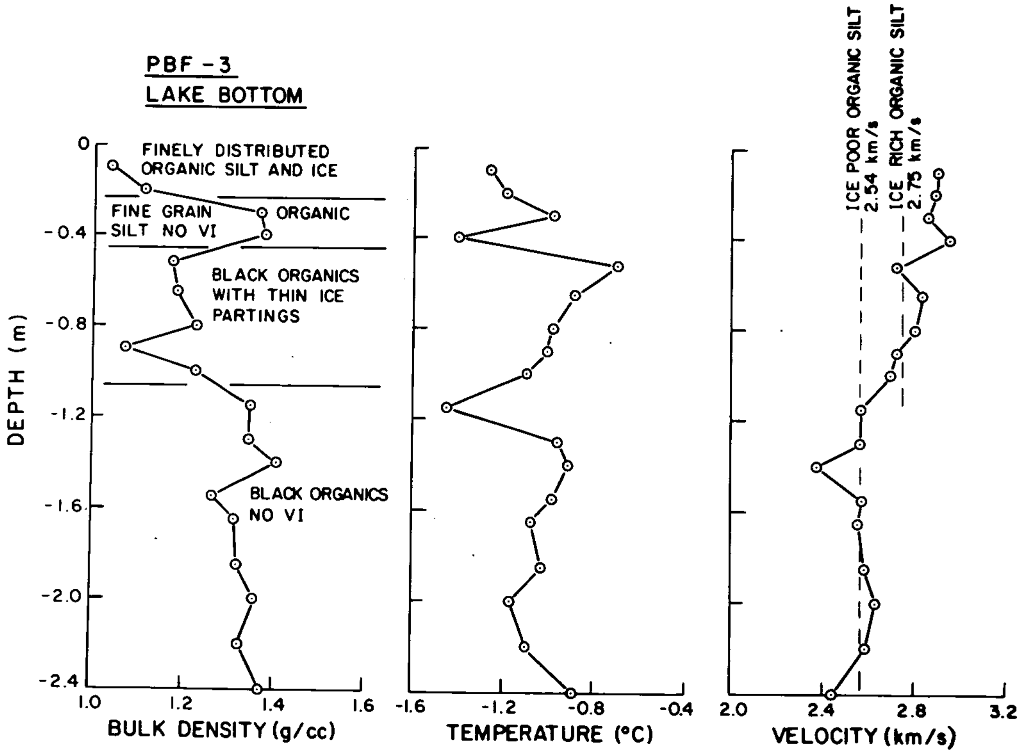

FIGURE 11. Borehole log for PBF-3.

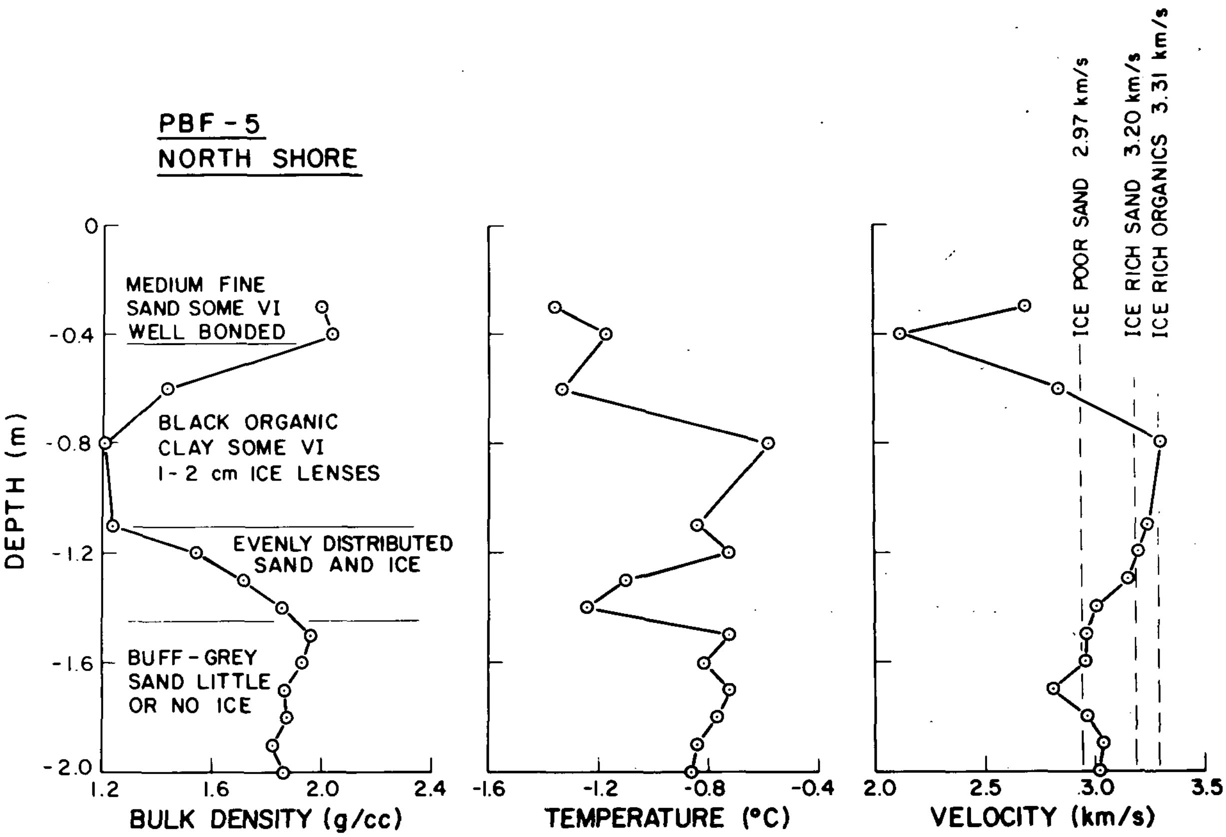

FIGURE 12. Borehole log for PBF-5.

velocity of 3.20 km/s. From the buried organic material, the area appears to be part of a solifluction lobe. The velocity of the organic material is approximately 3.31 km/s which is greater than that for the lake bottom organic material. This could be a function of the age of the ice or the distribution of the ice and mineral grains.

From the field data, it appears that there is a strong correlation between the velocity and bulk density. The velocity for ice-rich sediments increases with decreasing bulk density, however, the rate of increase is less than that established for the under-saturated soils.

Within a given borehole of consistent soil type and temperature, it should be possible to delineate ice-rich from ice-poor zones, based on acoustic logging. Low velocities would correspond to ice-poor zones, while the higher velocities would indicate relatively ice-rich sediments. A combined suite of geophysical logs, including, temperature, density, caliper, and acoustic measurements could provide a valuable interpretation tool for frozen soils.

Conclusions

The results of field and laboratory investigations show that the clay content of the soil governs the velocity where the soils have similar water contents. Clay-rich samples with low water contents show almost no reduction in velocity upon thawing, indicating that little of the soil moisture is bonding the soil grain together. Sand-rich soils exhibit a significant reduction in velocity upon thawing due to the ice-bonding of the grains. There appears to be a threshold bulk density, beyond which increases in moisture do not result in increases in bulk density. However, the addition of moisture results in substantial increases in the velocity. Once full saturation is attained, there is only a marginal increase in the velocity, with further increases in moisture content. Once the grain-to-grain contact is lost, the soil grains do not contribute significantly to the overall transmission of the compressional wave.

Field results from the four boreholes that were drilled in the sediments in and around Illisarvik lake, indicate that there is a shift towards higher velocities with increasing excess ice. However, extrapolation from one borehole to the next is rendered difficult due to the inconsistency of the results for similar soil types. Greater control of the temperatures taken during the velocity measurements may help to eliminate some of the variability. The velocities that were measured in the field were within the range of those obtained by surface seismic methods. This would, therefore, indicate that a correlation can be made between surface geophysical techniques and acoustic measurements. Calibration of the velocities for a given site through the use of acoustic techniques, may, in the future, help in the interpretation of field data. Work is currently in progress on the relationships between gamma-gamma and neutron response to massive ice. Since the gamma-gamma tool response is a function of bulk density, it should be possible to use calibrated acoustic and gamma-gamma logs to identify quantitatively, the volume of ice present in a given soil profile. With this information, extrapolation between holes should be possible, and then, borehole results can be used essentially to interpret surface seismic results.

Acknowledgements

Mr. A. Scott and Mr. F. Morrison, now with EBA Engineering Consultants, assisted in the collection of the field and laboratory data and their help in the project is gratefully acknowledged. The project was supported, in part, by a research grant from Energy, Mines and Resources.

References

BAKER, T.H.W. 1976. Preparation of artificially frozen sand specimens. Natl. Res. Counc., Div. Build. Res. Paper N. 682, Ottawa, 5 p.

MACKAY, J. ROSS, 1980. Drained lake experiments for investigation of the growth of permafrost in the western Arctic. *In:* Drained lake experiments for the investigation of the growth of permafrost in the western Arctic, a progress report prepared for the Permafrost Subcommittee, Natl. Res. Counc. (Ed. J.A. Hunter).