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SEISMIC CONE PENETRATION TESTING IN THE BEAUFORT SEA

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ABSTRACT

In the offshore environment the dynamic behaviour of seabed soil can be of great importance. Rapid development has taken place in the last decade on new analytical and dynamic testing techniques. The finite element method of analysis is now becoming a standard tool in dynamic and static design of complex structures both on and offshore. In order to obtain soil data for analysis, new field and laboratory testing techniques have been developed.

The dynamic shear modulus at small strain levels, G_{max}, can be determined using in-situ seismic methods for the measurement of the elastic shear wave velocity, V_s, since

$$G_{max} = \rho V_s^2$$

where ρ = soil density.
The cost of such a test using traditional crosshole or downhole methods is usually very high, especially offshore.

A new device, called a seismic cone penetrometer, can dramatically reduce the cost associated with seismic testing. Comparisons of seismic cone shear wave velocities with those measured by crosshole techniques at sites in Canada, Norway and the U.S. (Robertson et al, 1985) have validated the seismic cone technique.

This paper describes the design of the seismic cone penetrometer and discusses testing techniques and data interpretation. Results are presented from the seismic cone testing performed offshore in the Canadian Beaufort Sea. Details on alternate offshore techniques using the seismic cone are also discussed.

Results from the temperature sensor embedded in the cone penetrometer are also presented and discussed.

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INTRODUCTION

The in-situ soil testing research group of the Civil Engineering Department, University of British Columbia (UBC) was requested by the seismic methods section of the Geological Survey of Canada (GSC) to evaluate equipment, test procedures and techniques using a seismic cone penetrometer beneath the seafloor of the Beaufort Sea. The work was carried out near Tuktoyaktuk in the Northwest Territories on sea-ice during the period March to April, 1985. Generally, the thickness of sea-ice was about 2m.

Testing was carried out at four sites in and around the Tuktoyaktuk area. The locations of the four sites are shown in Figure 1. The Schoolhouse site was located in the near offshore area west of the hamlet of Tuktoyaktuk. A second site, referred to as Swimming Point, was located in the east channel of the Mackenzie River approximately 65 km south west of the hamlet of Tuktoyaktuk. The third site was located in Beluga Bay, west of North Point, Richards Island. This site will be referred to as the Richards Island site. The fourth site was located within the harbour at Tuktoyaktuk.

EQUIPMENT AND FIELD WORK

The field work was performed using the 110 kN (11 ton) research vehicle developed at the Civil Engineering Department, UBC. A complete description of the in-situ testing vehicle, its capacity, and hydraulic controls is given by Campanella and Robertson (1981). The vehicle was designed as a low cost, versatile vehicle for both research and teaching in the field.

Because of the Arctic environment of the project, major equipment modifications were necessary. Special equipment was developed for performing cone penetration tests on sea-ice. Support casing was provided from the truck floor to the mud line to prevent buckling of cone rods during penetration.

The research vehicle was used to perform seismic cone penetration tests (SCPT) in the seafloor of the Beaufort Sea. Full details of the design of an electronic cone are given by Campanella and Robertson (1981). An example of a UBC seismic cone penetrometer is shown in Figure 2. The cones have either a 10 cm or 15 cm base area with an apex angle of 60°. A friction sleeve, located behind the conical tip, has a standard

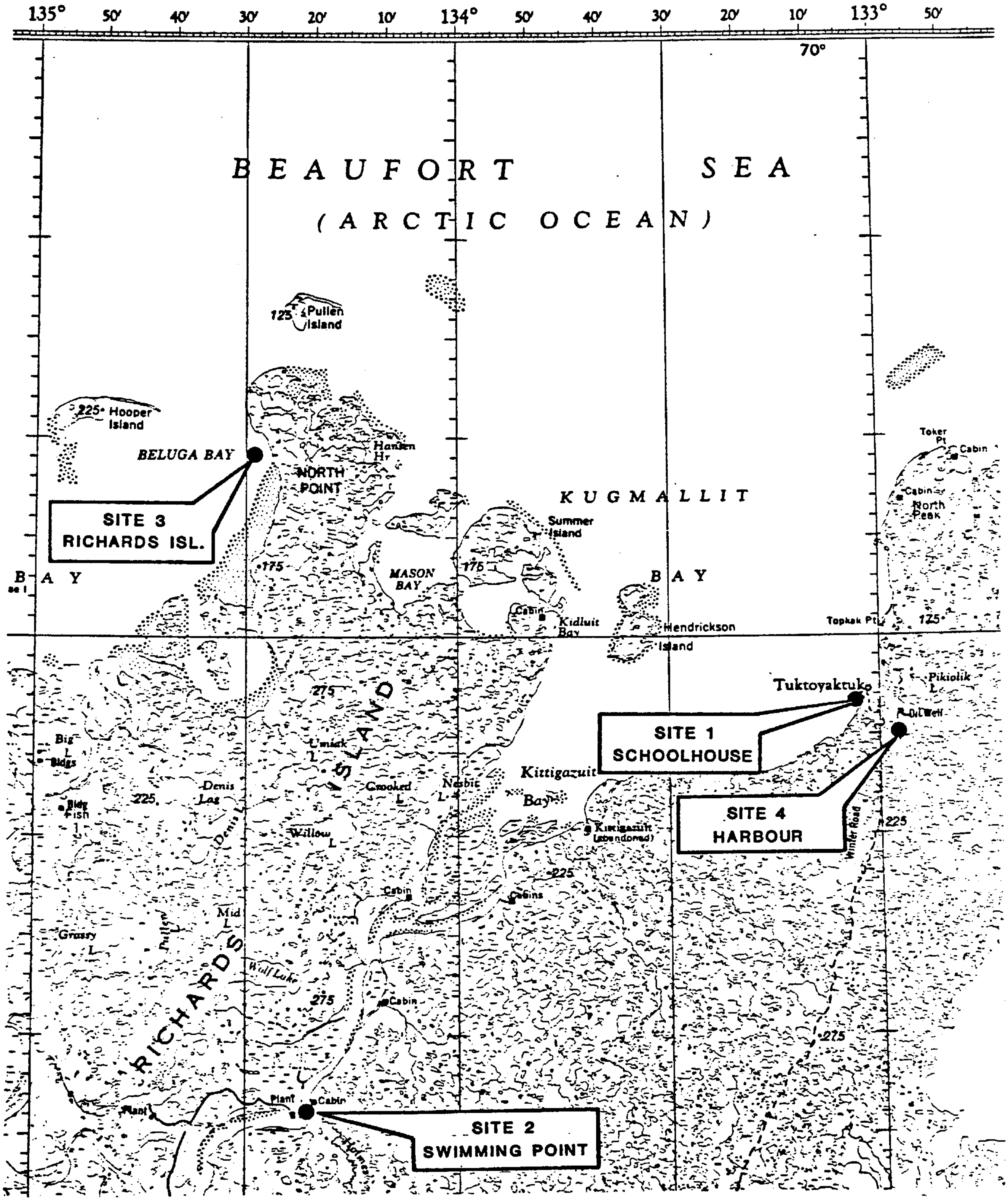

Fig. 1. Location Plan, Tuktoyaktuk Area, N.W.T., Canada

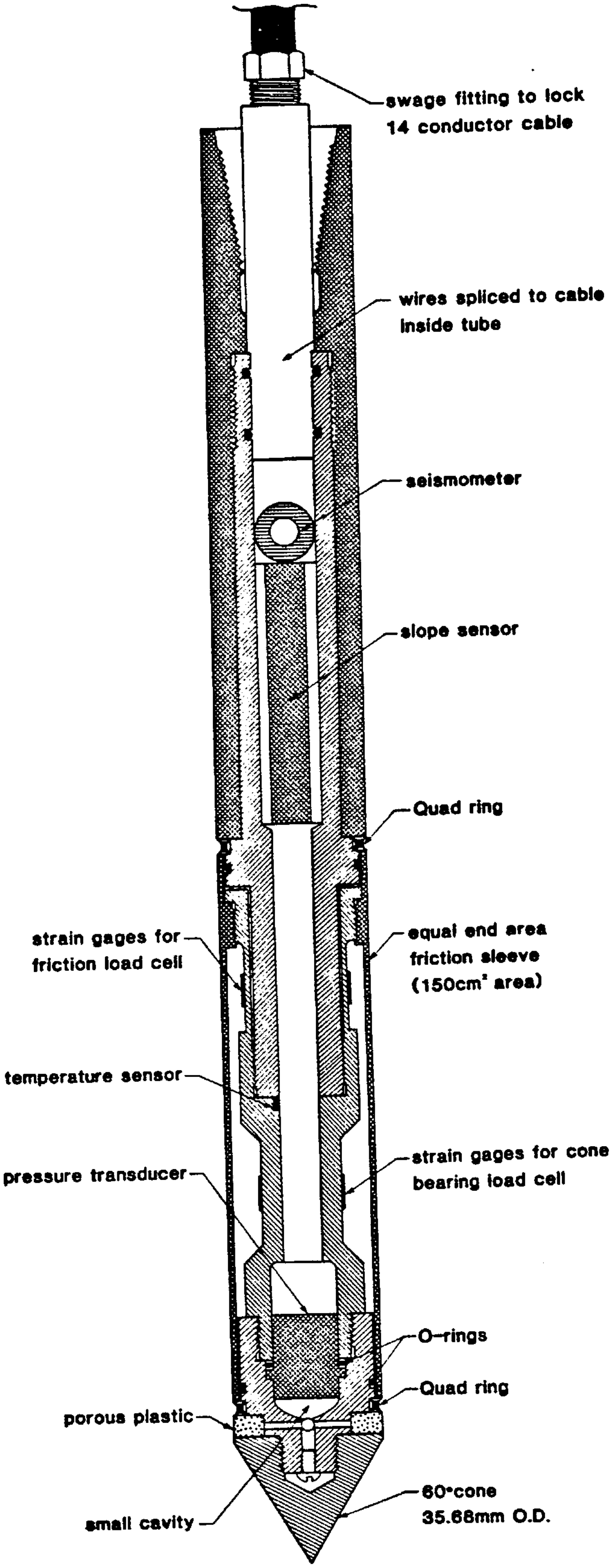

Fig. 2. Typical U.B.C. Seismic Cone Penetrometer

area of 150 cm for the 10 cm tip and 225 cm for the 15 cm tip. A pressure transducer is located inside the cone and can measure the pore pressure either on the face of the tip or immediately behind the tip. A new cone developed at UBC can simultaneously measure the pore pressure at two locations. One location is behind the friction sleeve, the other location can be either on the tip or immediately behind the tip. A temperature sensor is embedded in the cones, as shown in Figure 2. A slope sensor is also included in the cone design to monitor verticality during penetration.

To measure the seismic velocities, small rugged velocity seismometers as well as accelerometers have been incorporated into the cone penetrometer. The seismometer and accelerometer packages were either single or biaxial, horizontally orientated or horizontally and vertically orientated. Research has also been performed at UBC using triaxial packages (Rice, 1984), however, the cones used for this study were single or biaxial packages.

The design and construction of the seismometer carrier provides a snug seating for the seismometer package. The method of advancing the cone penetrometer provides continuous firm mechanical contact between the seismometer carrier and the surrounding soil. This allows excellent signal response. In addition, seismometer orientation can be controlled and accurate depth measurements obtained.

The seismic wave traces detected by the seismometer were recorded on a Nicolet 4094 digital oscilloscope with floppy disk capability. This unit has a 15 bit analog to digital signal resolution, very accurate timing capability and trigger delay capacity.

Several seismic sources were tested to evaluated their effectiveness in the generation of compressional and shear waves. Explosive caps were the predominant seismic source. The explosive caps where placed in a variety of ways. Generally, the caps where detonated at various depths in the water beneath the ice, as shown in Figure 3. However, several alternate methods were tested to place the caps into the seafloor using either a flat blade device or a circular plate.

When the sea-ice extended to the seafloor (i.e. no water beneath ice) the seismic signal was generated, as generally done on land, by striking the rear support pads of the research

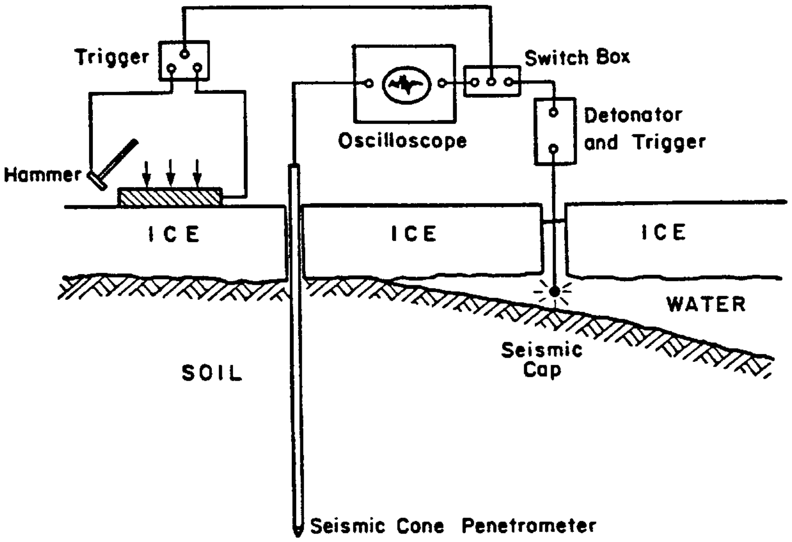

Fig. 3. Schematic of Hammer Shear Source on Surface and Seismic Cap Source

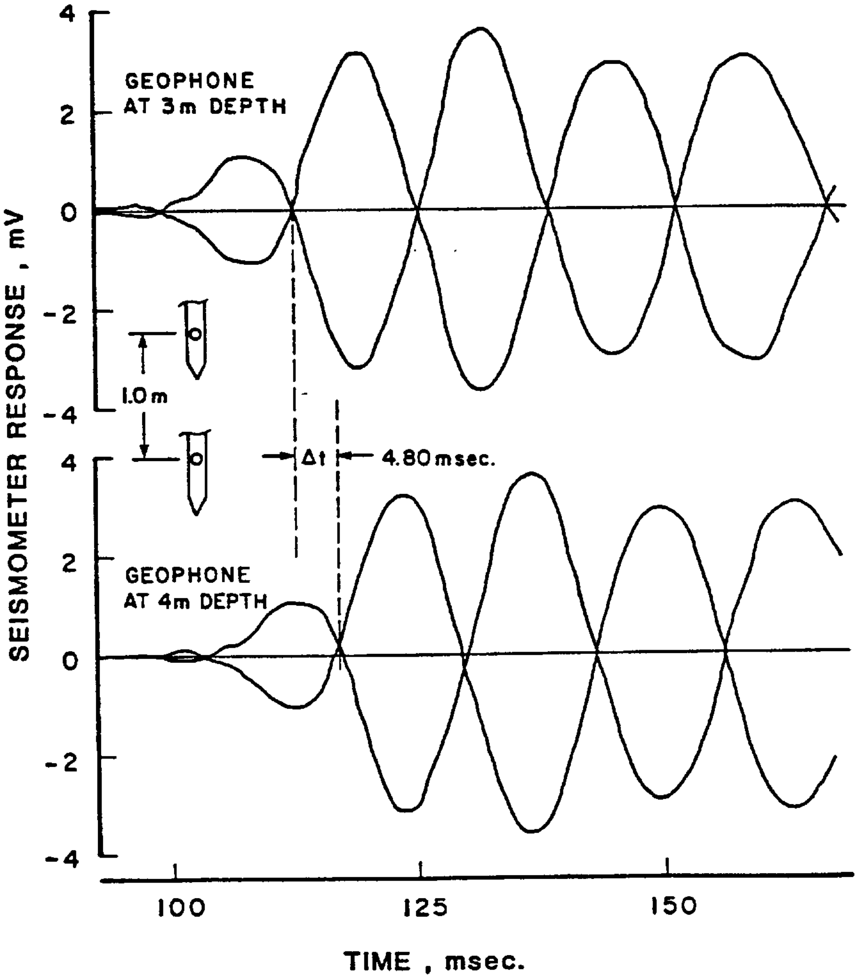

Fig. 4. Typical Polarized Shear Wave Signal Traces at 1 Meter Interval Depth Using Onshore Hammer Shear Source

vehicle with a 7 kg sledge hammer, as shown schematically in Figure 3. Using the hammer technique, it was possible to generate polarized shear (S) waves with very little compressional (P) waves.

SEISMIC CPT DATA AND INTERPRETATION

Seismic velocities are calculated using a pseudo-time interval technique (Rice, 1984). The arrival time from source to detector is converted vectorially to a vertical travel path. The difference between successive 1 m depth measurements of vertical travel path time is used to determine the wave travel time over the 1 m interval of depth. Generally, seismic measurements were made at 1 m intervals starting approximately 2 m below mudline. Because of the short distances and small travel times involved, the oscilloscope must have very high resolution, fast sample times and a very fast, repeatable trigger.

Figure 4 shows typical polarized shear wave signal traces obtained using the seismic CPT onshore with a hammer shear source. Figure 4 illustrates how the average shear wave velocity over a 1 meter depth increment is determined using the pseudo-time interval technique when the 1st major crossover is used as the reference for arrival times.

Typical results of the calculated seismic velocities obtained during this study are presented graphically in Figure 5. Included in Figure 5 is the cone penetration resistance proile to illustrate soil stratigraphy. The average P-wave velocity for all the soundings performed during this study was 1600 to 1700 m/s. Calculations using the pseudo-time interval method for high P-wave velocities are sensitive to small variations in seismic cap location. However, the small variations in travel path length had little influence on the calculation for the much slower S-wave velocity.

Good comparison had been achieved in previous studies between results using a single detector with the pseudo-time interval method and the true-time interval method using a pair of detectors 1 m apart. Good comparison had also been achieved in previous studies between shear wave velocities obtained using the seismic CPT using the hammer source and conventional onshore crosshole techniques (Robertson et al., 1985).

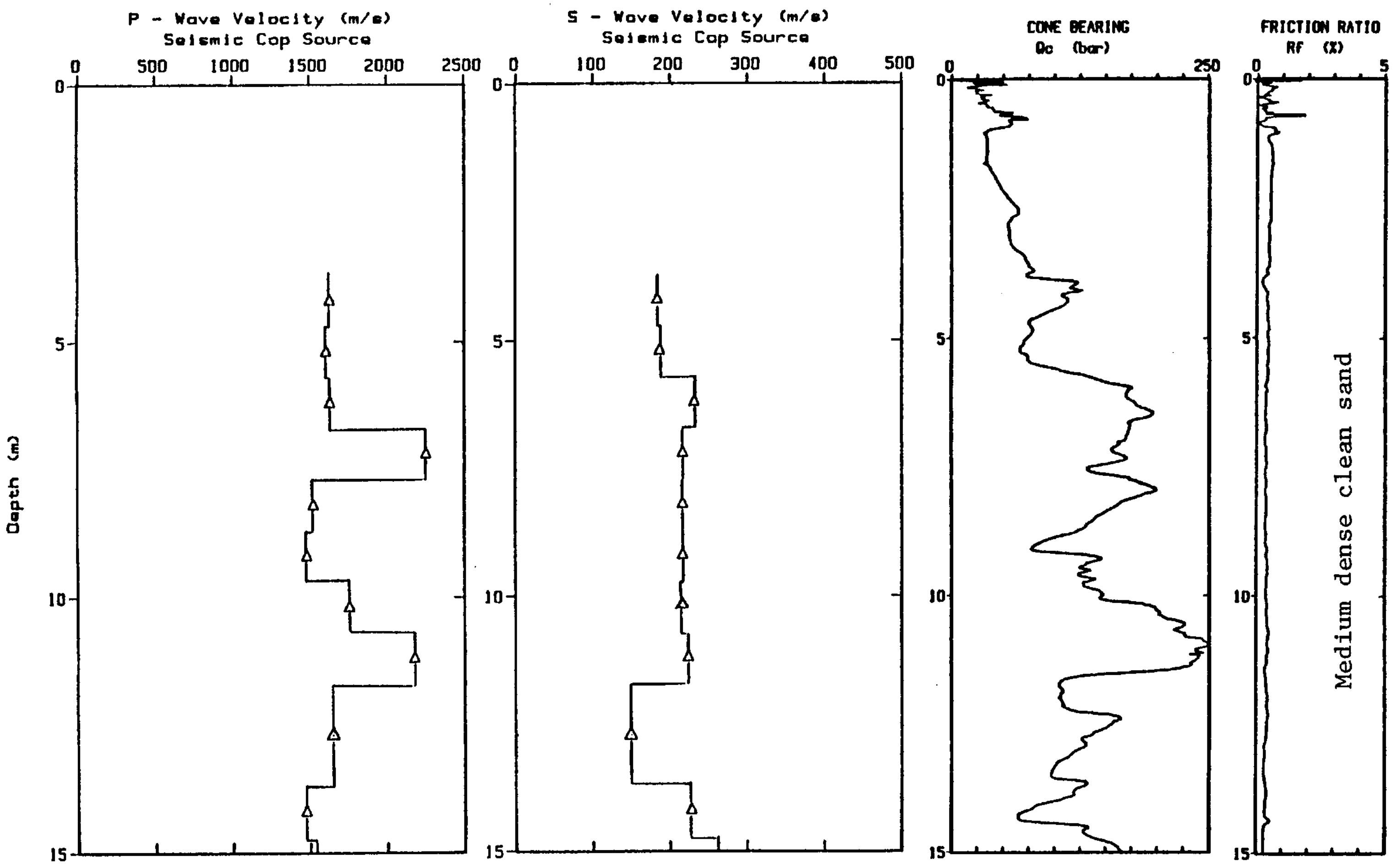

Fig. 5. Calculated Seismic Velocities and CPT Profile at Schoolhouse Site

Some difficulty was experienced in identifying the shear wave arrivals using the seismic cap source. Figure 6 illustrates the geophone response from depths of 4 m to 18 m at the Schoolhouse site shown in Figure 5. The fast, higher frequency P-wave arrivals are clearly visible. The slow, low frequency S-wave arrivals are also visible in Figure 6. The average shear and compression wave velocities shown in Figure 6 are 220 m/s and 1600 m/s, respectively. It is interesting to note the reflected P-wave arrivals in Figure 6. The depth of water beneath the sea-ice is less than a meter for the data presented in Figure 6. It appears the P-wave is reflected off the permafrost at a depth of 18.4 m below mudline then reflected again off the sea-ice.

At several locations the sea-ice extended down to and into the seabed. At these locations it was possible to use the hammer source to generate polarized shear waves through the ice and into the bonded soil with little compressional waves.

At one location at the Swimming Point site the depth to the mudline increased rapidly enough that it was possible to use both the hammer and seismic cap sources, as illustrated in Figure 3. A comparison of the shear wave velocities calculated using these independent energy sources is shown in Figure 7. Good comparison was achieved between the hammer source data and the seismic cap data. The data presented in Figure 7 provides some level of confidence in the procedure using the seismic cap source, although interpretation of the data is difficult.

Alternate seismic source methods were also evaluated in an effort to produce a predominantly shear wave source when water was present beneath the sea-ice. The most effective of these was a small blade embedded in the seabed with a seismic cap placed on one side. The concept of the blade was to produce an energy source similar to the hammer source used on land and shown in Figure 3. However, the blade was only effective if adequate confinement could be achieved. This required relatively soft soils at the mudline. At the Schoolhouse site the mudline soils were dense sands and the blade could not be embedded and was thus ineffective. However, at the Harbour site where the mudline soils were softer the blade was quite effective, as shown on Figure 8. The embedded blade technique was, however, very slow, especially for larger water depths.

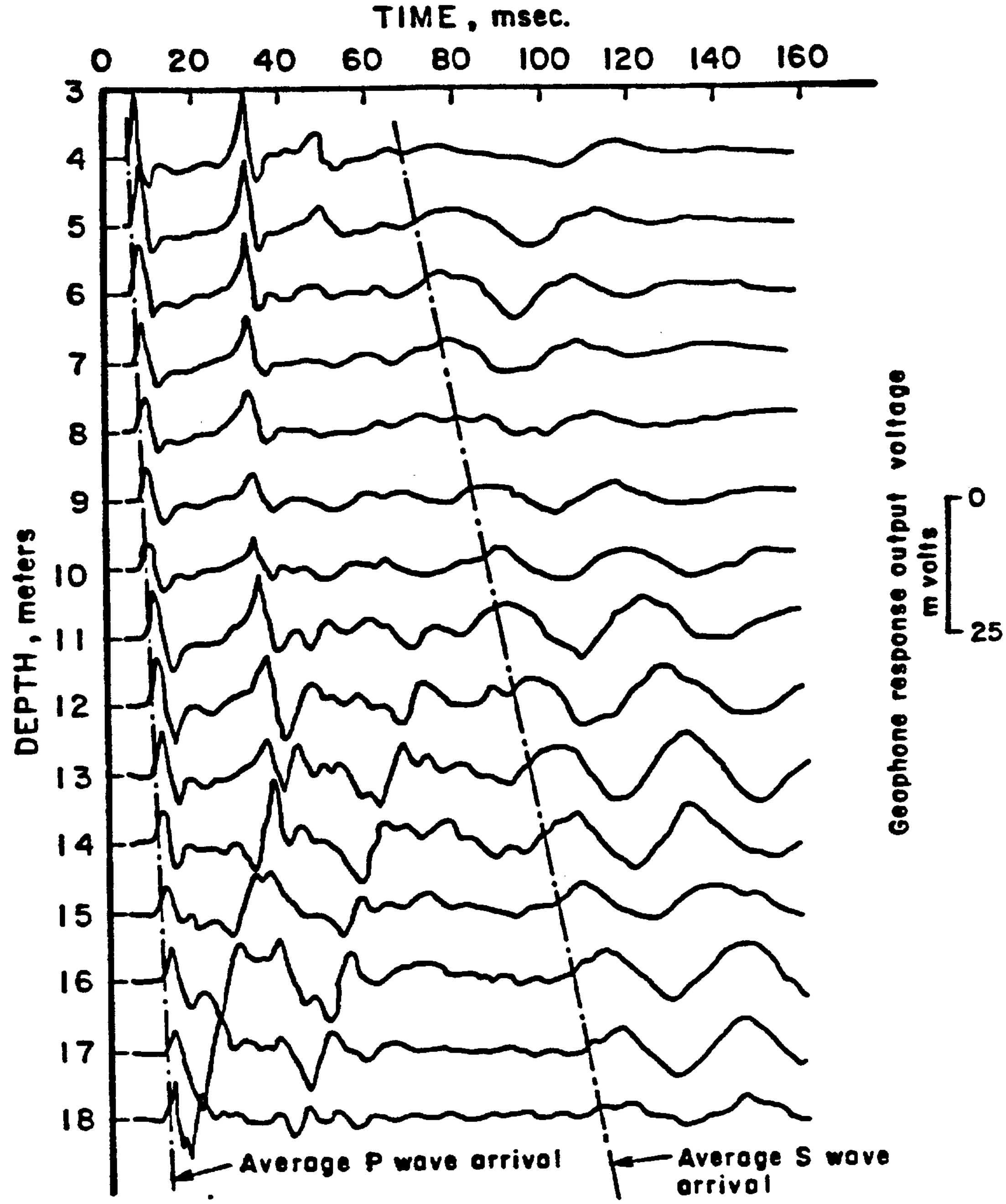

Fig. 6. Horizontal Geophone Response at 1 Meter Intervals From Seismic Cap Source Detonated in Water Beneath Sea Ice (Schoolhouse Site, Tuktoyaktuk, N.W.T.)

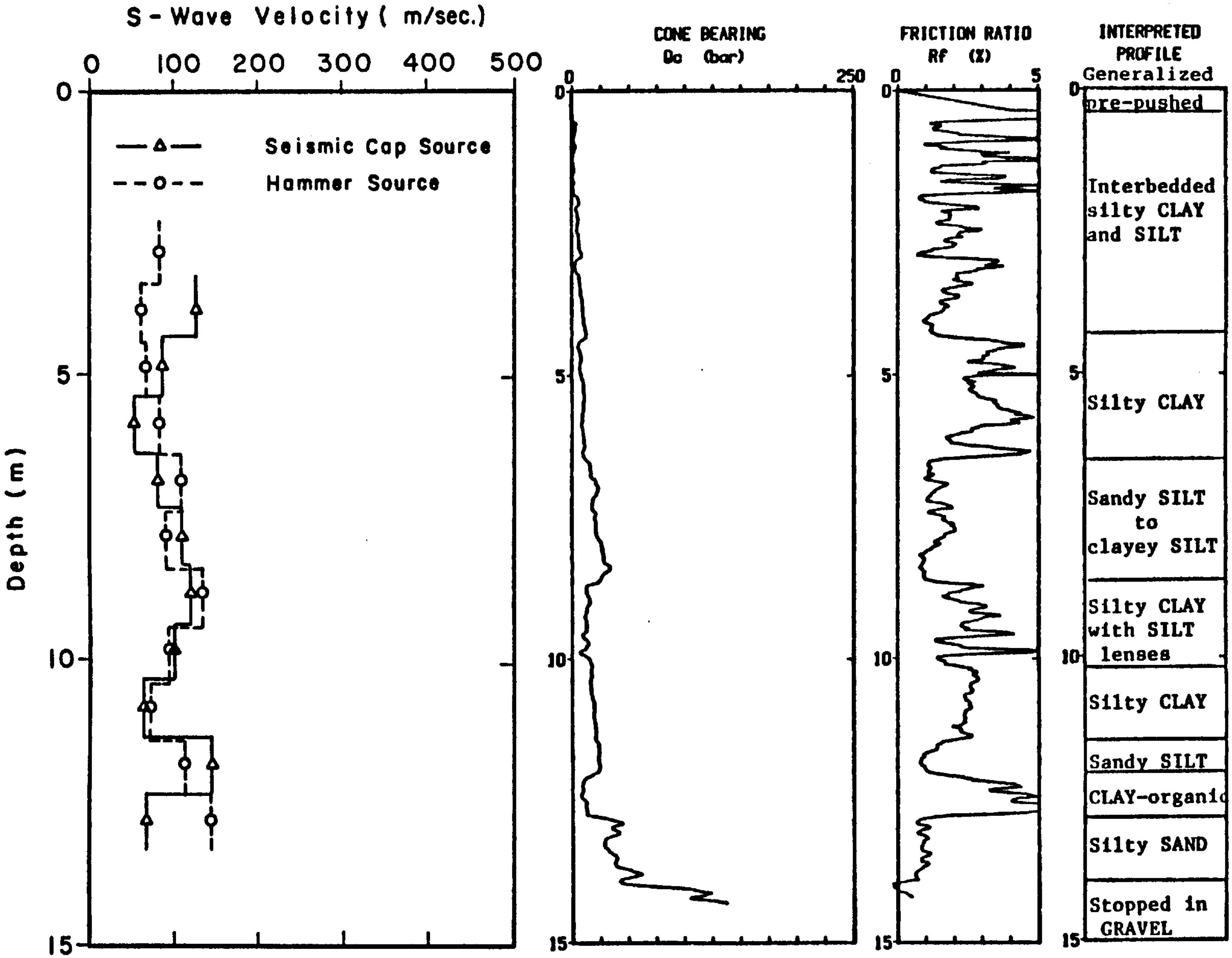

Fig. 7. Comparison of Interpreted Shear Wave Velocities From Hammer Shear Source on Surface and Seismic Cap Source in Water at Swimming Point

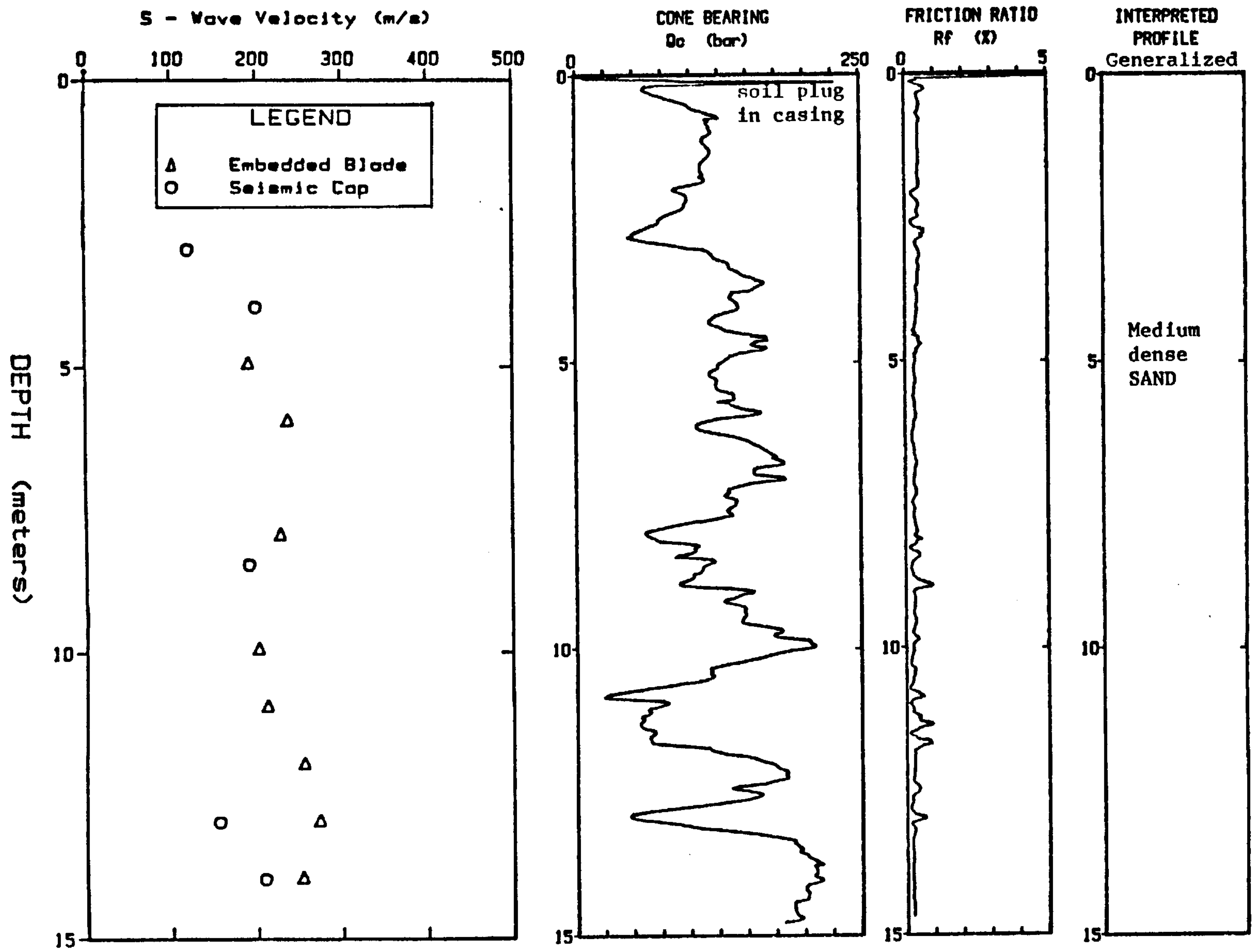

Fig. 8. Comparison of Shear Wave Velocity by Embedded Blade and Seismic Cap Shear Source at Harbour Site, Tuktoyaktuk, N.W.T.

CPT TEMPERATURE PROFILES

A typical CPT temperature profile obtained from a sounding at the Richards Island site is shown in Figure 9. The plot shows the temperature measured in the cone after a short time period of temperature dissipation. Typical waiting time was about 3 minutes with a maximum waiting period of about 13 minutes. Dissipation times in seconds are recorded next to each data point. During the dissipation period, the temperature recorded would typically rise a small amount then fall. Recorded temperatures were generally continuing to fall when penetration was resumed.

Figure 2 shows that the temperature sensor was located in the central part of the cone. Experience has shown that during cone penetration, heat is generated along the surface of the cone. In dense sands, significant heat generation can result, especially above the water table. The temperature profiles shown in Figure 9 indicate that some heat is generated during cone penetration in the Beaufort seabed deposits. Figure 9 clearly shows that penetration through the dense sand at the Richards Island site, between 4 m and 8 m has generated at least 4°C of temperature and that this heat is not dissipated within a time period of about 3 minutes. Figure 9 also shows that penetration through the clayey soils above and below the sand has generated little heat. In general when penetration was stopped in permafrost the cone temperatures were close to 0°C. CPT temperature data obtained at the Swimming Point site showed that although the soils at Swimming Point are soft, temperatures recorded in the cone seem high. This may represent the warming influence of the Mackenzie River.

The rise in temperature immediately after a pause in cone penetration may be caused by the response time of the system since the sensor is near the centre of the cone close to the strain gauges (Figure 2). Thus, time is required for the temperature sensor to rise toward the temperature that exists on the surface of the cone and then considerably more time is required for the sensor to reach the equilibrium temperature of the surrounding soil.

SUMMARY AND CONCLUSIONS

In general, the basic cone penetration testing was extremely successful and provided excellent stratigraphic detail at each site.

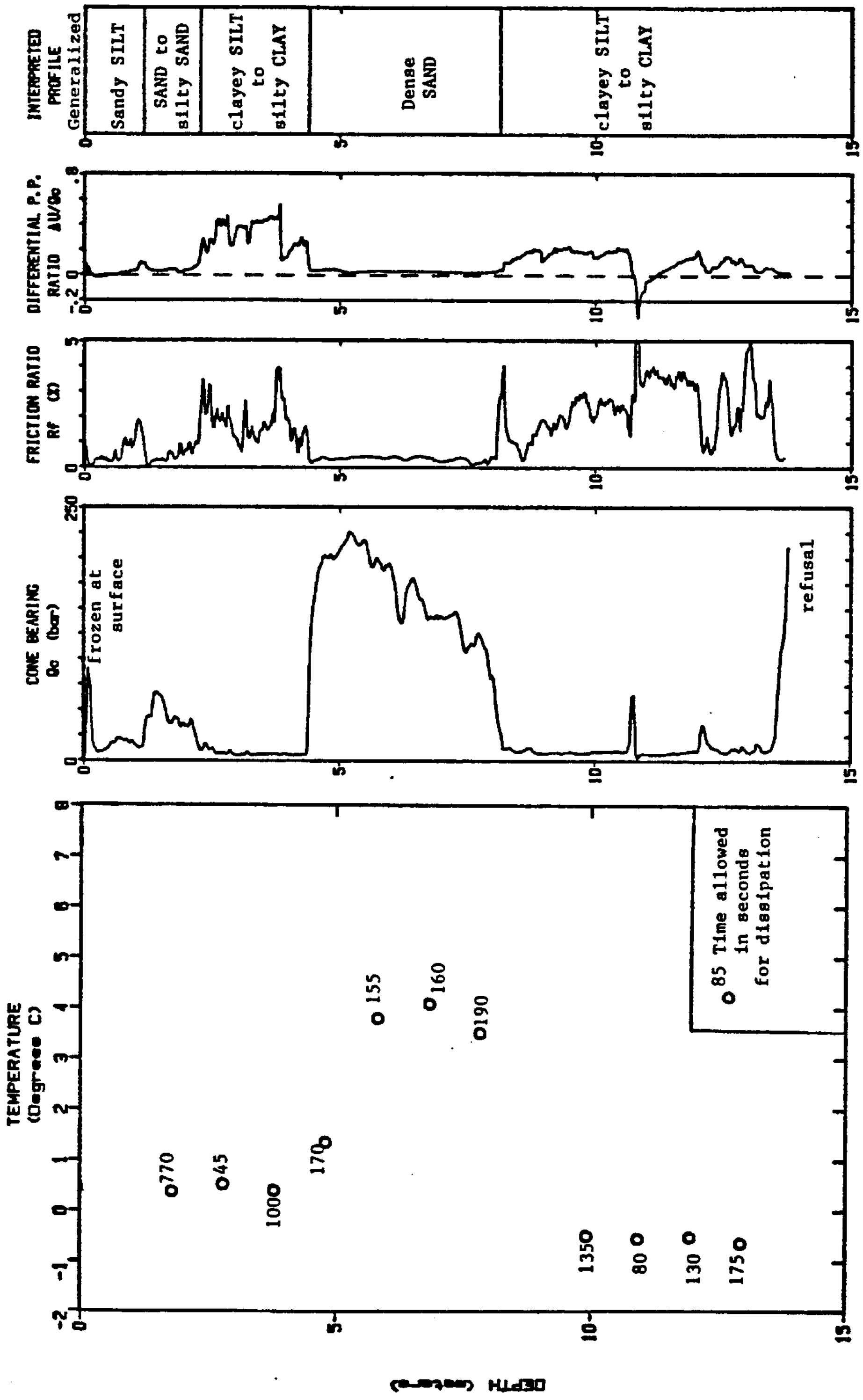

Fig. 9. Temperature After Dissipation - Richards Island

The seismic testing was also successful. Good seismic shear wave velocity profiles were determined at each site. Evaluation of the different seismic techniques and equipment used are discussed in the next section as well as the observed temperature response.

Seismic Receiver: Both geophone and accelerometer devices were tested as a suitable receiver. Generally, the unfiltered geophone provided the best data for shear wave arrival because of its relatively high damping and low resonance (28 Hz). An example of this data is shown in Figure 6. Experience at the UBC research site in Vancouver, however, has shown that accelerometers can produce accurate response data for the soil if adequate filtering is provided. Unfortunately, the filtering system evaluated during this study was not the most suitable. Also, the accelerometer response was influenced by the very high energy of the seismic cap and the undamped accelerometer causing severe ringing or resonance at about 1000 Hz. Digital filtering and wave analysis techniques are currently being evaluated to interpret the accelerometer response. Both geophones and accelerometers were able to detect P-wave arrivals. However, because of the high velocity of the P-waves the pseudo-time interval technique for calculation of interval velocity is very sensitive to slight variations in seismic cap location.

The vertically oriented geophones and accelerometers were unable to detect P- or S-wave arrivals. The vertically oriented devices appeared to respond only to high frequency signals travelling within the stiff cone rods.

Significant improvement could be made in the type of accelerometer and its filtering. Installation of two horizontally oriented receivers, orthogonal to each other, would eliminate the necessity for orientation of receiver and source. This is especially useful when seismic sources are placed on the sea floor and orientation cannot be controlled.

The use of two horizontally oriented receivers spaced 1 m apart in the cone rods would allow the true-time interval technique to be used to calculate seismic velocities. This would avoid problems of variable seismic source location for calculation of P-wave velocities. However, this would complicate the equipment somewhat. It may be simpler to continue with the single package of seismic receivers placed in the cone but control the seismic source location more carefully.

Seismic Source: The seismic caps used during this study produced a very high energy and thus large amplitude P-waves. This tended to create a ringing in the receiver which was not fully damped before arrival of the S-wave. This was especially noticable at shallow depth. By moving the seismic cap off the mudline, a larger time separation and smaller P-wave amplitude was achieved.

Alternate seismic source methods were also evaluated in an effort to produce a predominantly S-wave source. The most effective of these was a small blade embedded in the seabed with a seismic cap placed on one side. However, the blade was only effective if adequate confinement could be achieved. The embedded blade technique was, however, very slow, especially for larger water depths.

In general, the explosive cap detonated beneath the ice provided acceptable data for interpretation of P- and S-wave velocities. However, interpretation of the S-wave arrivals was difficult (see Figure 6) and required careful interpretation. The CPT profile provided useful additional data to assist in the interpretation.

For shallow penetration (i.e. less than 5 m below mudline) both geophone and accelerometer data is difficult to interpret due to the short time separation between the large amplitude P-wave arrival and the lower amplitude S-wave arrival (see Figure 6). This problem could be reduced if the energy level of the source is smaller or if a predominantly S-wave source is used.

When the sea-ice extended down to and into the seabed, the hammer technique (Figure 3) was effective. Reasonable response was obtained in spite of the fact that the sea-ice was not always completely bonded to the seafloor sediments. Good comparison was achieved between the hammer source data and the seismic cap data (Figure 7) indicating that the travel path assumption is correct. The Swimming Point site offered a unique opportunity to compare the two techniques because of the rapidly increasing depth to mudline.

Improvements could be made in the seismic source. Smaller (lower energy) seismic caps or exploding bridge wire should be evaluated. A simple seabed shear wave source is presently under development at UBC and will be evaluated offshore shortly.

Temperature Response: The temperature measurements taken during cone penetration and pauses in the penetration indicate that significant heat is generated during penetration and that considerable time is required for the temperature to stabilize at the in-situ equilibrium temperature. The temperature sensor for the UBC cones is located near the center of the probe which may have slowed the time required for temperature equalization. The original purpose for the location of the temperature sensor was to permit possible corrections to load cell output due to temperature variations (Campanella and Robertson, 1981).

The time allowed for temperature dissipation during this study was generally not sufficient to allow full equalization to in-situ temperature. Therefore, the temperature profiles obtained probably do not represent in-situ equilibrium temperatures. Temperature sensors placed very near the outside surface of the cone would equilibrate to the in-situ soil temperature much more rapidly.

Although the seismic CPT has worked well in the Beaufort Sea environment, there are several modifications to equipment and test procedures that could be made to improve the technique. These modifications are continuing and require further evaluation.

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