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Seismic cone penetration testing in the near offshore of the MacKenzie Delta

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A study was performed in the shallow waters of the MacKenzie Delta area near Tuktoyaktuk, N.W.T., Canada, to evaluate equipment, test procedures, and techniques using a seismic cone penetrometer and operating on the landfast ice in winter. Seismic cone penetration testing was performed to determine the compressional and shear wave velocities of the subsurface sediments using a downhole technique. Several seismic sources and receivers were tested to evaluate their effectiveness. Typical results are presented and briefly discussed.

Key words: downhole, seismic, P-wave, S-wave, velocity, *in situ*, measurement, shallow offshore, cone penetration test.

Une étude a été réalisée dans les eaux peu profondes du Delta du MacKenzie près de Tuktoyaktuk (T.N.-O.), Canada, pour évaluer l'équipement, les procédures et les techniques d'essai utilisant un pénétromètre séismique et opérant sur la glace de rive en hiver. Des essais de pénétromètre séismique ont été exécutés pour déterminer la vélocité des ondes de cisaillement et de compression des sédiments souterrains utilisant une technique de mesure dans le trou de sondage. Plusieurs sources et récepteurs séismiques ont été étudiés pour évaluer leur efficacité. Des résultats typiques sont présentés et discutés brièvement.

Mots clés : mesure en forage, séismique, onde P, onde S, vélocité, *in situ*, mesure, offshore peu profond, essai de pénétration au cône.

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Introduction

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

$$[1] \quad G_{\max} = \rho V_s^2$$

where ρ = soil density.

The cost of such a seismic test using traditional crosshole or downhole methods (Woods 1986) is usually very high because of the need for drilling and special equipment and procedures, especially offshore.

A new device, called a seismic cone penetrometer, can dramatically reduce the cost associated with seismic testing, especially if cone penetration testing (CPT) is used as part of the regular site investigation program. Comparisons of onshore seismic cone shear wave velocities with those measured by crosshole techniques at sites in Canada, Norway, and the U.S. (Robertson *et al.* 1986) have already validated the seismic cone technique.

This note presents and briefly discusses results from seismic cone testing performed in the shallow offshore in the MacKenzie Delta area, Northwest Territories, Canada.

Equipment and fieldwork

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 sea floor of the near shore Beaufort Sea in the MacKenzie Delta area. The work was carried out near Tuktoyaktuk in the Northwest Territories on landfast sea ice during the period March–April, 1985. Generally, the thickness of sea ice was about 2 m.

Testing was carried out at four sites in and around the Tuktoyaktuk area. The locations of the four sites are shown in Fig. 1. The schoolhouse site was located in the near offshore area west of the hamlet of Tuktoyaktuk. A second site, referred to as the swimming point site, was located in the east channel of the MacKenzie River approximately 65 km southwest 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. At each site one borehole and from one to five seismic cone penetration tests were carried out.

The seismic cone fieldwork 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 multiple casing (115 mm outer diameter and 50 mm inner diameter) was hung from the truck floor to the mud line to prevent buckling of cone rods during penetration.

A typical UBC seismic cone penetrometer is described and shown in Robertson *et al.* (1986). The cones used have either a 10 or 15 cm^2 base area with an apex angle of 60°. A friction sleeve, located behind the conical tip, has a standard area of

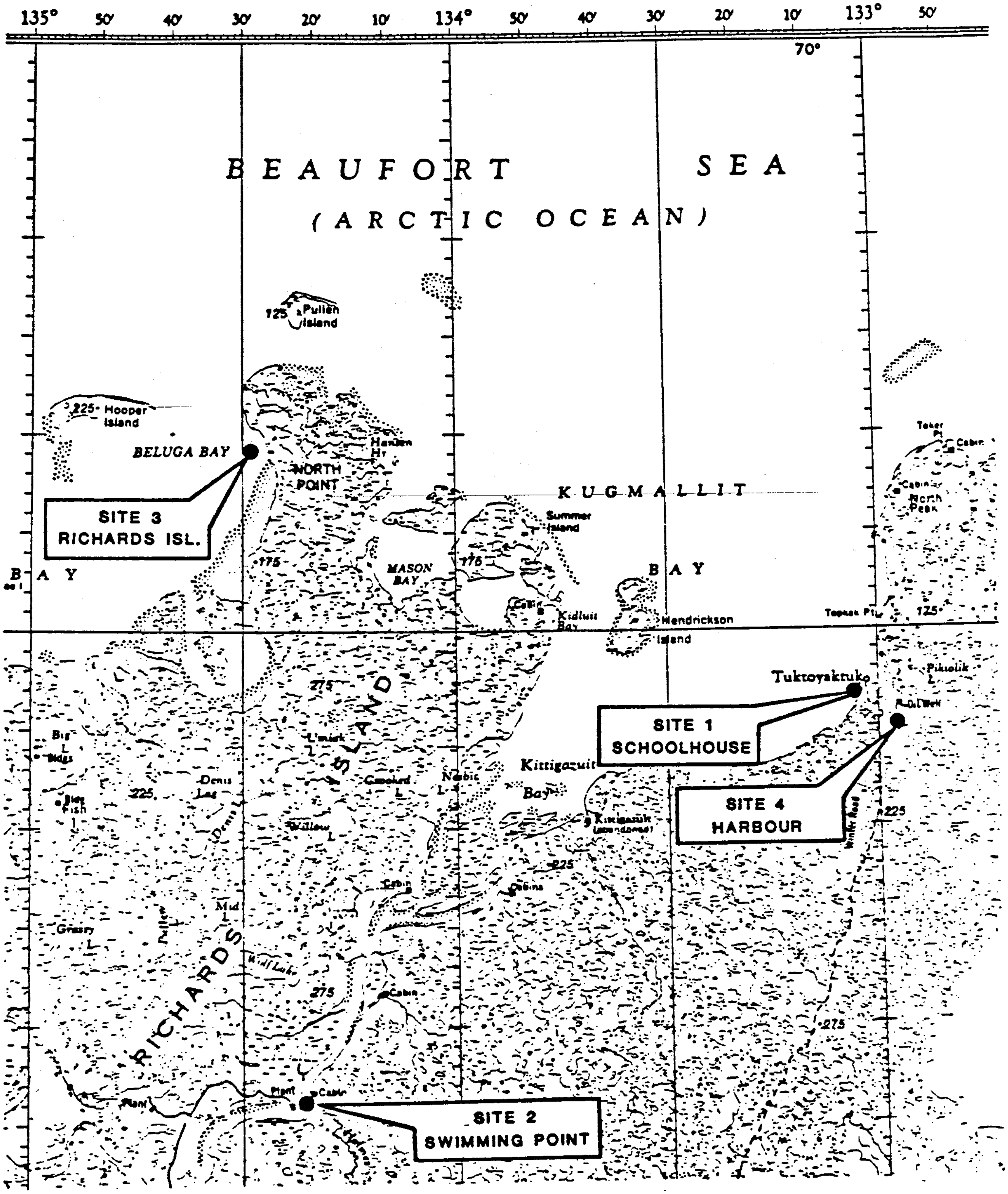

FIG. 1. Location plan, Tuktoyaktuk area, N.W.T., Canada.

150 cm² for the 10 cm² tip and 225 cm² for the 15 cm² 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 also 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 also embedded in the cones, which is primarily used to correct data for thermal offset. A slope sensor is also included in the cone design to monitor verticality during penetration.

To measure the seismic velocities, small rugged magnetic

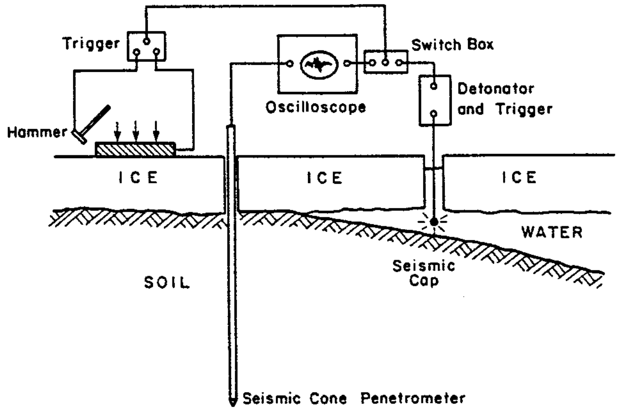

FIG. 2. Schematic of hammer shear source on surface and seismic cap source.

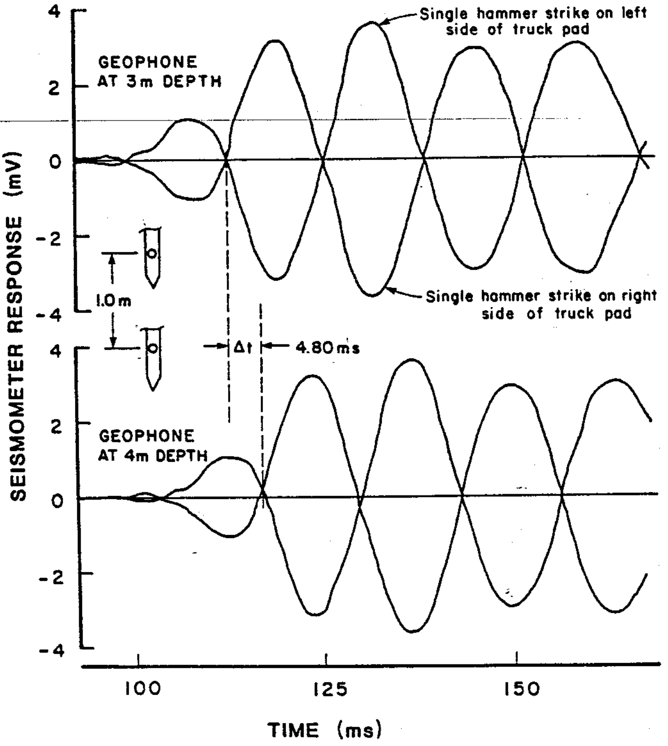

FIG. 3. Typical reversed polarized shear wave traces at 1 m interval depth using onshore hammer shear source.

coil velocity seismometers (resonance ≈ 28 Hz) were embedded into the cone penetrometer. Some cones used piezoelectric bender acclerometers (resonance ≈ 1000 Hz) instead. 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 either single or biaxial packages.

The design and construction of the seismometer carrier provide 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 coupling and therefore exceptionally good 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 evaluate their effectiveness in the generation of compressional and shear waves. Explosive caps were the predominant seismic source. The explosive caps were placed in a variety of ways. Generally, the caps were detonated at various depths in the water beneath the ice, as shown in Fig. 2. However, several alternate methods were tested by placing the caps into the sea floor using either a flat-blade device or a circular plate.

When the sea ice extended to the sea floor (i.e. no water beneath ice) the seismic signal was generated, as generally done on land, by striking the rear support pad of the research vehicle with a 7 kg sledge hammer, as shown schematically in Fig. 3. Using the hammer technique, it was possible to generate reversed polarized shear (S) waves with very little compressional (P) waves by horizontally striking the truck pad on opposite sides of the vehicle (see Fig. 3).

Seismic CPT data and interpretation

Seismic velocities are calculated using a pseudo-time interval technique (Rice 1984). The travel time from source to detector is converted vectorially to a vertical travel path. The difference between successive depth measurements of vertical travel path time is used to determine the wave travel time over that interval of depth. The first crossover of polarized shear waves has been found to give the most repeatable reference arrival (see Fig. 3). When using explosive cap sources, it is not possible to reverse polarization, and arrival times are visually estimated. Generally, seismic measurements were made at 1 m intervals starting approximately 2 m below mud line. 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.

Typical results of the calculated seismic velocities obtained from the schoolhouse site during this study are presented graphically in Fig. 4. Included in Fig. 4 is the cone penetration resistance profile to illustrate soil stratigraphy. The CPT and adjacent borehole data showed that the soils at the schoolhouse site (Fig. 4) were predominately medium dense clean sand.

The average P-wave velocity for all the soundings performed during this study was 1600–1700 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. In previous studies good comparison had also been achieved between shear wave velocities obtained using the seismic CPT using the hammer source and conventional onshore crosshole techniques (Robertson *et al.* 1986).

Seismic source

Some difficulty was experienced in identifying the shear wave arrivals using the seismic cap 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 that was not fully damped before arrival of the S-wave.

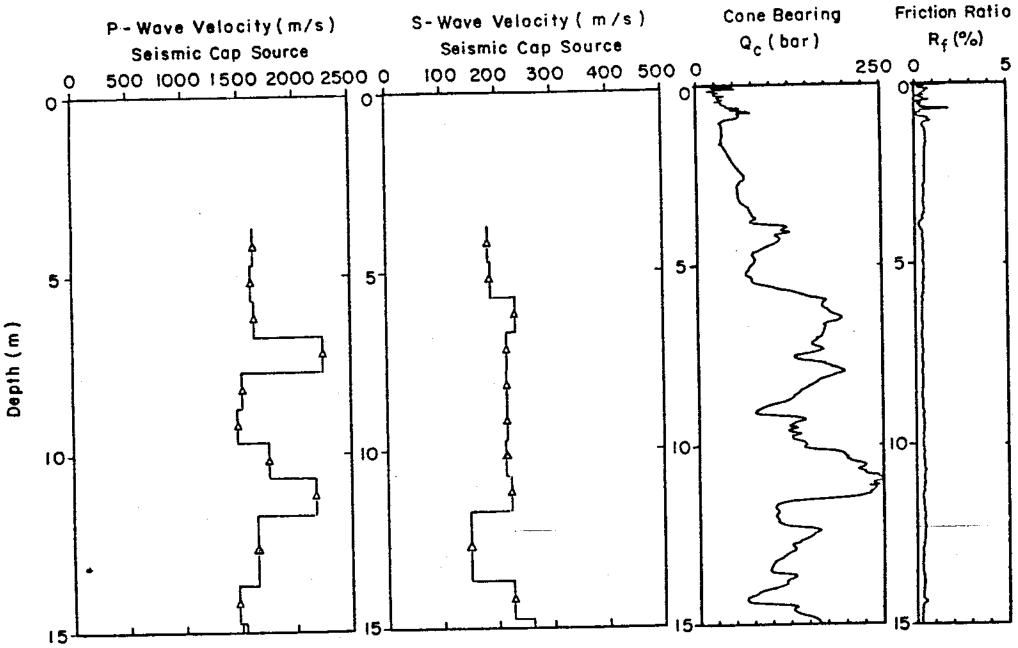

FIG. 4. Calculated seismic velocities and CPT profile at schoolhouse site using seismic cap source.

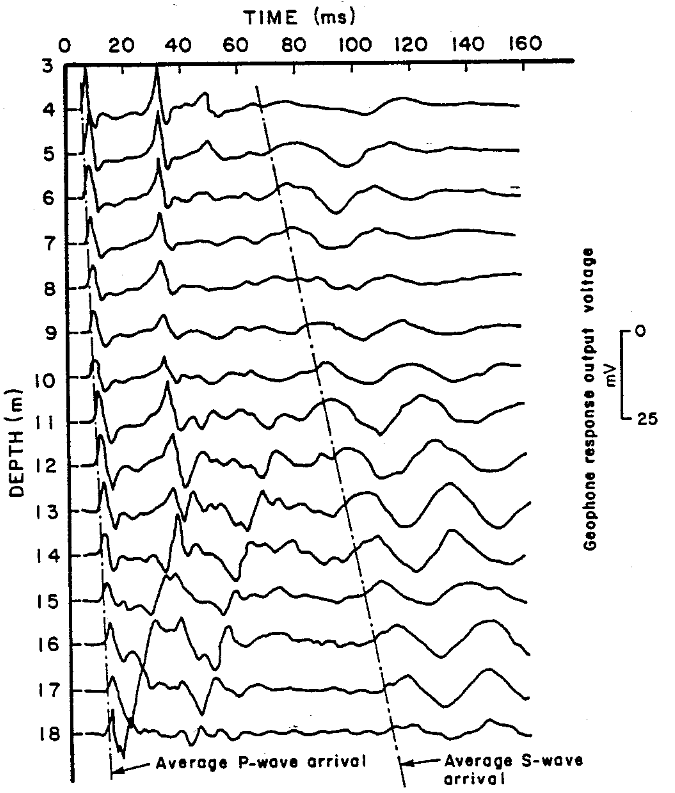

FIG. 5. Horizontal seismometer response at 1 m intervals from seismic cap source detonated in water beneath sea ice (schoolhouse site, Tuktoyaktuk, N.W.T.).

This was especially noticeable at shallow depth. By moving the seismic cap off the mud line, a larger time separation and smaller P-wave amplitude were achieved.

Figure 5 illustrates the seismometer response from depths of 4–18 m at the schoolhouse site shown in Fig. 4. The fast, higher-frequency P-wave arrivals are clearly visible. The slow, low-frequency S-wave arrivals are also visible in Fig. 5. The average shear and compression wave velocities shown in Fig. 6 are 220 and 1600 m/s, respectively. It is interesting to note the reflected P-wave arrivals in Fig. 5. The depth of water beneath the sea ice is less than a metre for the data presented in Fig. 5. It appears the P-wave is reflected off the permafrost at a depth of 18.4 m below mud line 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 reversed 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 mud line increased rapidly enough that it was possible to use both the hammer and seismic cap sources, as illustrated in Fig. 3. A comparison of the shear wave velocities calculated using these independent energy sources is shown in Fig. 6. Fair to good comparison was achieved between the hammer source data and the seismic cap data. The data presented in Fig. 6. provide some level of confidence in the procedure using the seismic cap source, although interpretation of the data is difficult. The shear wave velocities in the soft clays and silts at the swimming point site (Fig. 6) were about 100 m/s or about half those in the medium dense sands at the schoolhouse site (Fig. 4).

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 Fig. 3. However, the blade was only effective if adequate confinement could be achieved. This required relatively soft soils at the mud line. At the schoolhouse site the mud line soils were dense sands and the blade could not be embedded and was thus ineffective. However, at the harbour site where the mud line soils were softer the blade was quite effective and shear wave velocity measurements by blade

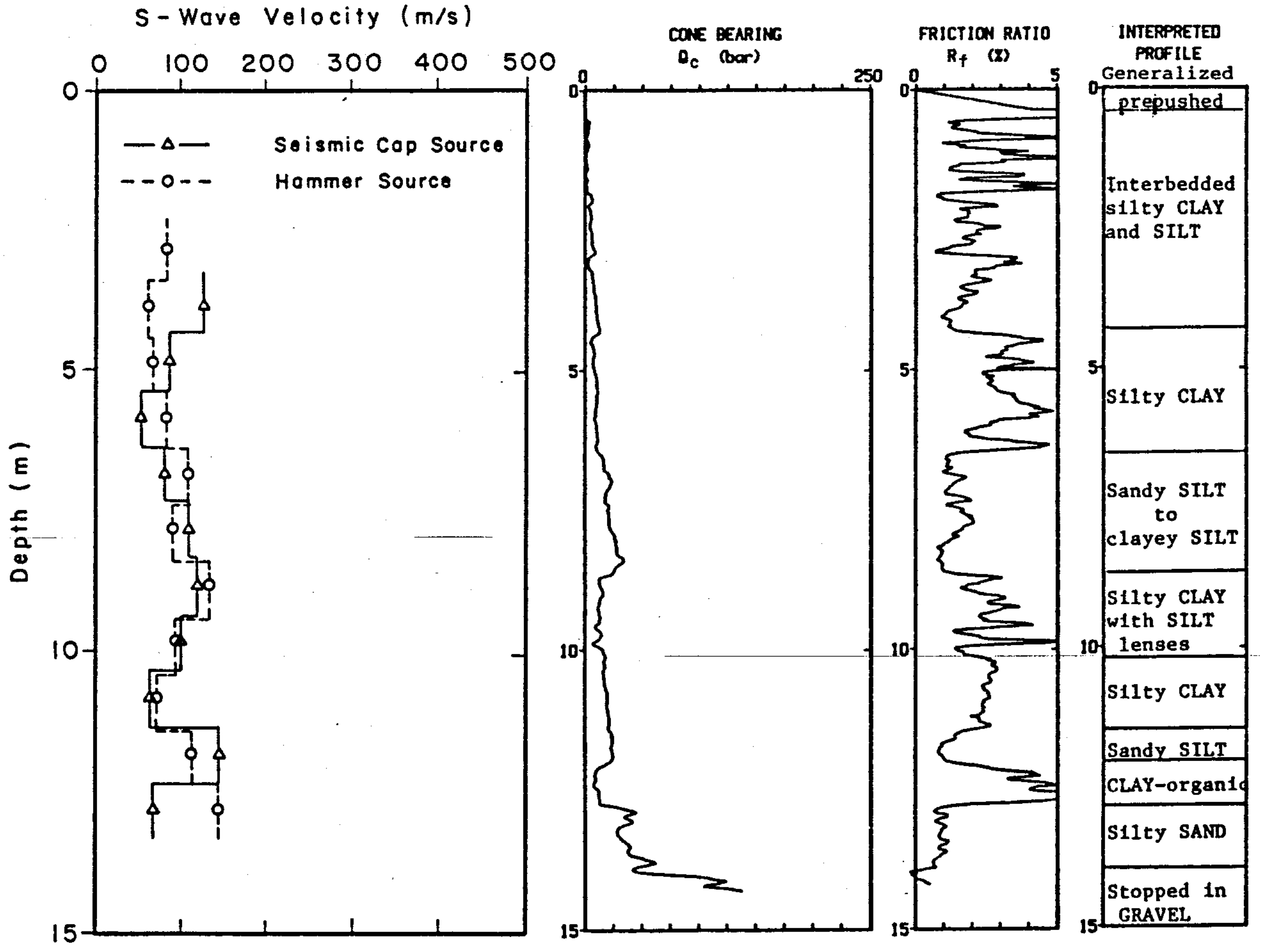

FIG. 6. Comparison of interpreted shear wave velocities from hammer shear source on surface and seismic cap source in water at swimming point site.

source and seismic cap source compared favourably, as shown in Fig. 7. The embedded-blade technique was, however, very slow, especially for larger water depths.

In general, the explosive cap, when 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 Fig. 5) 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 mud line) both seismometer and accelerometer data are difficult to interpret owing to the short time separation between the large-amplitude P-wave arrival and the lower-amplitude S-wave arrival. This problem could possibly be reduced if the energy level of the source is reduced or if a predominantly S-wave source is used. A simple seabed impulse shear wave source is presently under development at UBC and will shortly be evaluated offshore.

Seismic receiver

Both seismometer and accelerometer devices were tested as suitable receivers. Generally, the unfiltered seismometer 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 Fig. 5. 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 available 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 studied to interpret the accelerometer response. Both seismometers 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 seismometers and accelerometers gave response signals that did not consistently allow visual interpretation of P- or S-wave arrivals. The vertically oriented devices appeared to respond also to high-frequency and high-velocity signals travelling within the stiff steel cone rods.

Summary

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

The seismic testing was also successful. Seismic wave velocity profiles were determined at each site and yielded an average value for compressional (P) and shear (S) wave velocities of 1600–1700 and 220 m/s respectively. These values compared well with seismic wave velocities measured on core samples obtained from adjacent boreholes.

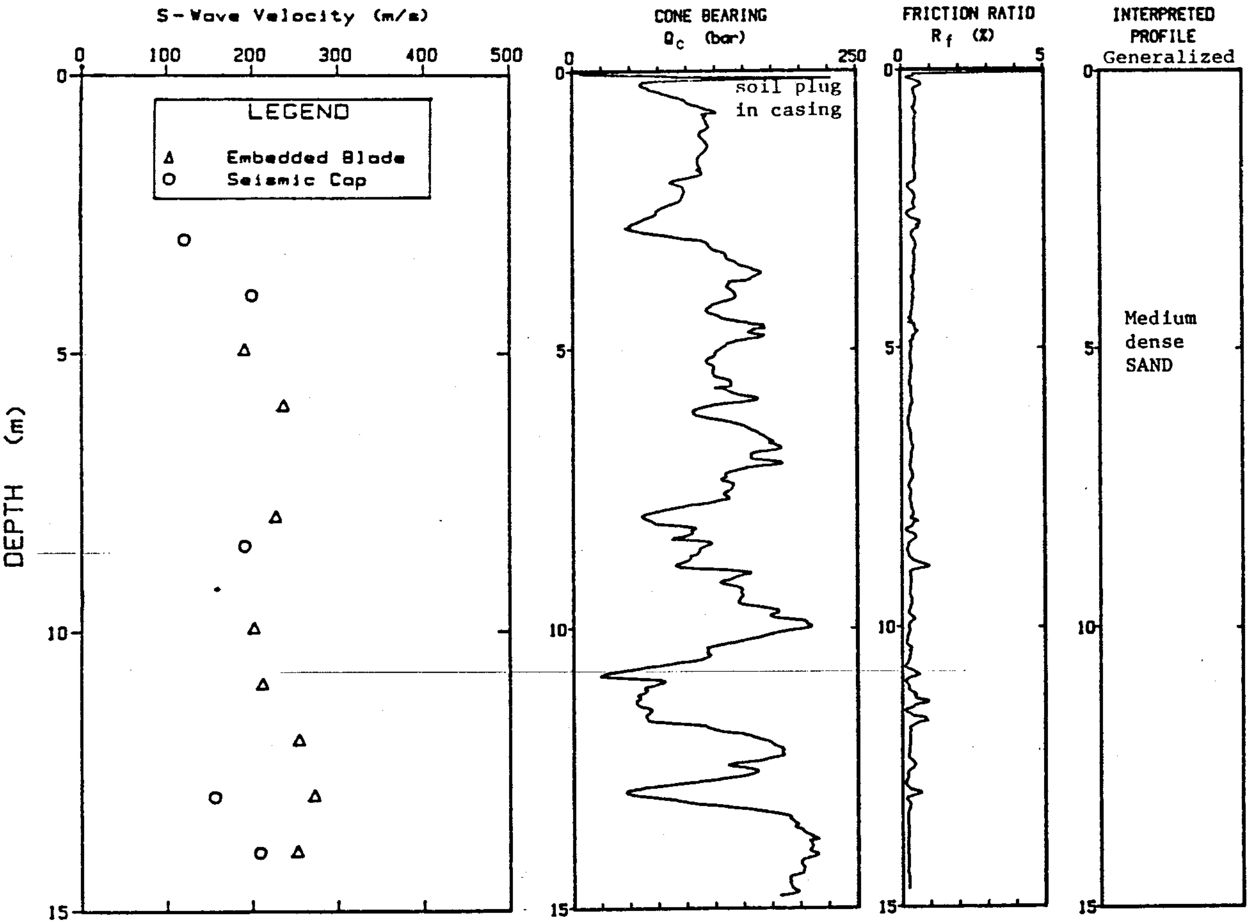

FIG. 7. Comparison of shear wave velocities by embedded-blade and seismic cap source at harbour site.

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