Cone penetration tests of arctic marine sediments

Essais de sédiments marins arctiques par pénétromètre conique

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SYNOPSIS: Modified electric cone penetrometers have been used to record stratigraphy, temperature, acoustic velocities and N values of marine sediments in the near-shore zone of the continental shelf. The results show excellent agreement with those measured in the geotechnical boreholes and on recovered core samples.

1. INTRODUCTION

The coastal areas of the southern Beaufort Sea form a large region of coastal lowlands in northern Canada. Anticipated development of hydrocarbon resources discovered in sedimentary basins underlying this area has created an unprecedented need for detailed knowledge of the geological, geotechnical and geothermal conditions of the nearshore zone sediments. Detailed data are required for the engineering design and construction of structures such as pipelines and marine terminals, related to the development of oil fields.

The Geological Survey of Canada has carried out detailed geotechnical investigations at several sites in the nearshore zone off Richards Island and Tuktoyaktuk Peninsula since 1984.

The measurements of geotechnical, geophysical and geothermal parameters of the marine sediments using the cone penetrometer, and interpretation of obtained results, are the main aspects discussed in this paper. A general site location map of the geotechnical programs, documented by Kurfurst (1984, 1986, 1988), is shown in Figure 1.

2. EQUIPMENT AND FIELD PROCEDURES

The cone penetration tests (CPT) were carried out either by the In-situ Testing Group of the Department of Civil Engineering, University of British Columbia, or by ConeTec Investigations Ltd., both of Vancouver, British Columbia. A standard 10 ton Hogentogler subtraction electrical cone, either equipped with seismometers, as described by Campanella and Robertson (1984), or specially modified using the platinum resistance temperature detectors (RTD), as discussed by Kurfurst and Woeller (1988), were used throughout the programs.

The cones are capable of recording cone tip resistance (Q_c), sleeve friction (F_s), dynamic pore pressure (U_t), cone inclination (i), temperature (T), and compressional (P) and shear (S) wave velocities.

Most of the cone penetration soundings were located 3 to 5 m from the geotechnical boreholes to avoid any possible disturbance caused by drilling, but sufficiently close to obtain meaningful and reliable comparison of results. A typical example showing locations of geotechnical boreholes and cone penetration tests is given in Figure 2.

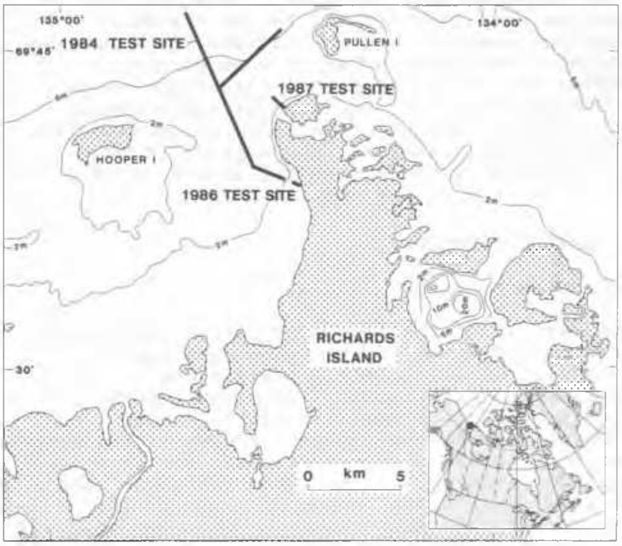

Figure 1: Site location plan.

Prior to each cone penetration, a hole was augered through sea ice and steel casing was set to the mud line in order to prevent buckling of the cone rods during penetration. The cone was either deployed from a specially equipped test truck or pushed by means of a modified drill rig; both vehicles allow an application of down-pressure up to 10 tons.

Geotechnical boreholes were drilled prior to the cone penetration tests using either an HT-700 or CME 750 hydraulic top-drive rotary drill. Standard penetration tests (SPT) were performed when possible, and boreholes were sampled with either a 7.6-cm diameter Shelby tube sampler or a 12-cm diameter CRREL core barrel. All core samples were immediately

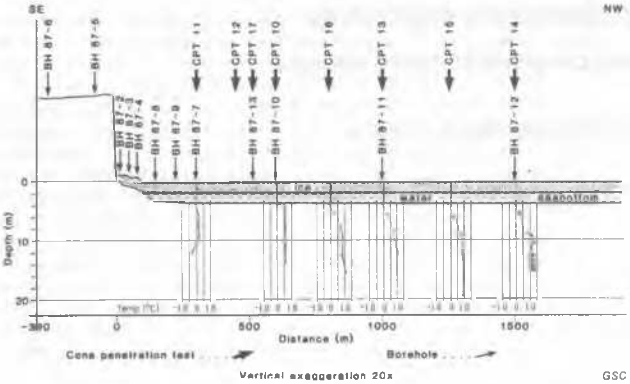

Figure 2. Location of boreholes and CPT soundings.

logged, soil and ice type descriptions were made, and temperature and pocket penetrometer (PP) readings were recorded. Selected core samples were retained for future standard physical analysis and specialized tests such as acoustic and shear strength measurements. Thermistor cables were then installed in all boreholes to record equilibrium temperatures and compare them with the temperature data from the cone penetrometer. The depth of cone penetrometer soundings ranged from 8 to 20 m below the top of the sea ice.

3. DATA INTERPRETATION

3.1 Stratigraphy

The results of the cone penetration tests were interpreted using correlations developed by Robertson et al. (1986) to obtain the encountered soil types. The stratigraphic interpretation is based on relationships amongst cone bearing, sleeve friction, friction ratio and dynamic pore pressure. The friction ratio is a calculated parameter which is used to infer soil type. Interpretation of the results of cone penetration tests shows that the soils in the nearshore zone consist of a thin layer of soft clayey silt which occurs from the mudline to depths of 2 m and grades into organic-rich silty clay with increased distance from the shore. This silt and clay are underlain by a thick deposit of massive, fine-grained sand which becomes dense with increased depth.

The soil stratigraphy inferred from the cone penetration test data compares well with the soil stratigraphy determined from the geotechnical borehole data. Accurately defined boundaries of various lithological units also correspond well with those determined by means of the borehole core logging. Comparable stratigraphic logs from the geotechnical borehole 87-12 and the adjacent cone penetration test CPT 14 are displayed in Figure 3.

3.2 Temperature

Soil and sea water temperatures were taken during each cone penetration test. Because substantial amounts of heat were generated along the surface of the cone, especially in cohesionless soils with high sleeve friction

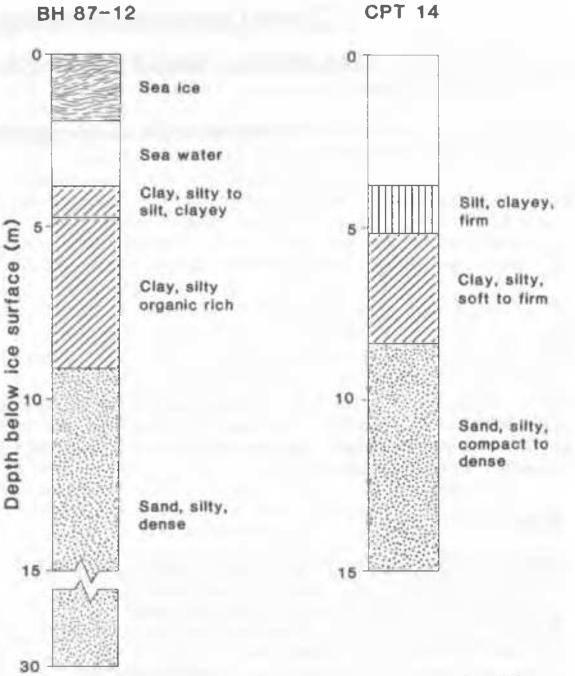

Figure 3. Stratigraphic logs - BH 87-12 and CPT 14.

values, changes in temperature with time were recorded and a dissipation time of 600-900 seconds was established as sufficient in order to obtain accurate ambient equilibrium temperatures. Detailed discussion of the equipment and procedures used is given by Kurfurst and Woeller (1988).

Temperature records obtained at various depth intervals show that the ambient temperature of the sea water at the mudline is relatively constant at -0.2°C. However, soil temperature profiles indicate that ground temperatures increase with depth and then gradually decrease with increased proximity to the permanently frozen sediments.

The temperature data from the cone penetration test were compared with the data from the thermistor cable. Thermistor cables were installed in all geotechnical boreholes and were monitored at regular intervals until thermal equilibrium was reached. When the cone temperature data are compared with the thermistor cable data, an excellent agreement with variations of less than ±0.2°C exists. Comparison of typical temperature data measured by means of a thermistor cable in borehole 87-7 and by a cone penetrometer in the adjacent hole CPT 11 is shown in Figure 4.

3.3 Acoustic velocities

Compressional (P) and shear (S) wave velocities were recorded in the field, using accelerometers located within the cone penetrometer, and calculated using the technique described by Campanella and Robertson (1984). The measurements were then repeated on core samples from the geotechnical boreholes adjacent to the cone penetration test holes using equipment and techniques discussed by Kurfurst and Pullan (1985).

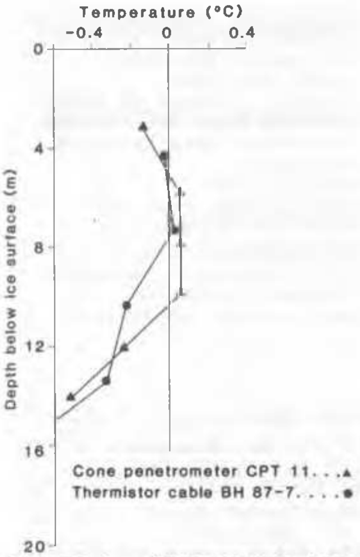

Figure 4. Temperature logs - BH 87-7 and CPT 11.

The average field compressional wave velocities measured by the cone penetrometer were between 1600 and 1700 m/s; the maximum velocity recorded was about 2300 m/s. The shear wave velocities averaged about 220 m/s. The compressional wave velocities measured on the core samples in the laboratory ranged from 1400 to 2400 m/s, and the shear wave velocities varied between 220 and 360 m/s. Comparison between field compressional wave velocities recorded by the seismic cone penetrometer and velocities measured in the laboratory is shown in Figure 5.

Uphole seismic measurements were also made in all geotechnical boreholes and were used to interpret interval compressional velocities as a function of depth. The results confirmed excellent correlation with the seismic cone and laboratory data, as discussed in detail by Kurfurst and Pullan (in press).

3.4 Undrained shear strength

The cone penetration tests (CPT) and the standard penetration tests (SPT) were carried out in five geotechnical boreholes in order to obtain a reliable N value (number of blows/30 cm) and a range of undrained shear strength of the cohesive marine sediments. In addition, approximate values of shear strength were measured using the pocket penetrometer (PP) on core samples from the boreholes where the CPT and SPT were carried out.

N values were used to classify the sediments using the SPT correlation chart (Acker, 1974) and the Modified National Building Code. The CPT and SPT undrained shear strength ranged from 48 to 192 kPa at depths to 8 m below sea ice, then increased to 388 kPa with increased depth to about 25 m below sea ice. Significantly higher values (>388 kPa) were encountered at depths between 25 and 34 m below the ice surface. Values of shear strength measured by the pocket penetrometer, although considered less reliable, showed a good agreement with the CPT and SPT data.

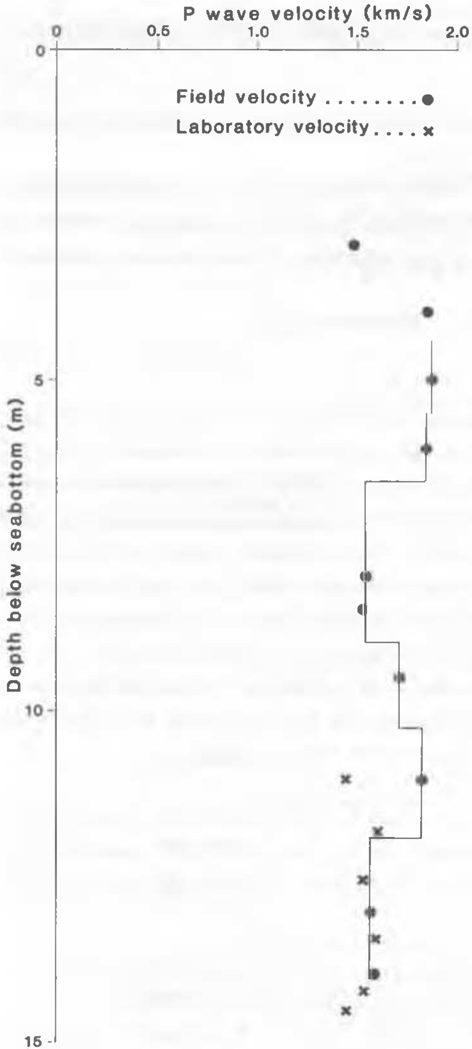

Figure 5. Field and laboratory P-wave velocities.

Comparison between the CPT, SPT and PP-derived shear strength values is presented in Figure 6.

A distinct zone of high shear strength, overconsolidated sediments at depths ranging from 25 to 34 m below the ice surface has been detected throughout the study area. Overconsolidation of the marine sediments can be caused possibly by sedimentation rate, thermal regime, cementation, thaw consolidation and cyclic wave loading, as discussed in detail by Christian (1985). Due to lack of reliable data, it can be speculated only that thaw consolidation is an important mechanism causing overconsolidation of these sediments in the study area. For example, it is known that Beaufort Sea sediments deposited in the deltaic environment are prone to repeated cycles of freezing and thawing, which can cause higher preconsolidation pressure upon reloading. This mechanism is directly related to the seasonal fresh-water discharge of the Mackenzie River.

4. SUMMARY AND CONCLUSIONS

A modified electrical cone has been used to

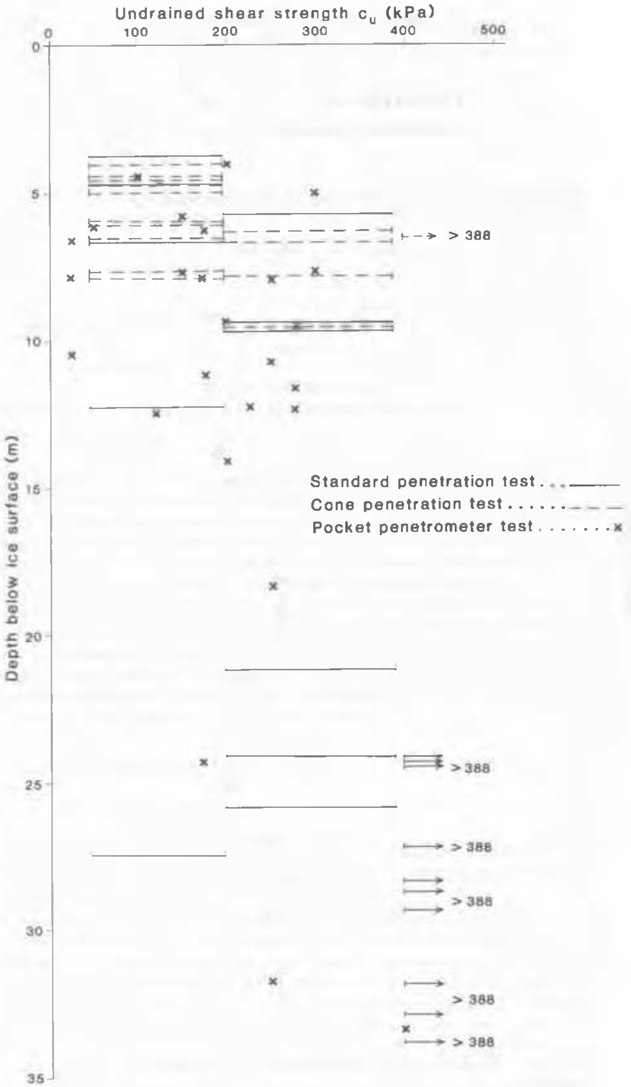

Figure 6. Undrained shear strength logs.

record accurate profiles of temperature, acoustic velocity and shear strength and to obtain stratigraphic information of the marine sediments in the nearshore zone of southern Beaufort Sea.

The soil stratigraphy inferred from the results of the cone penetration test was compared with that determined from geotechnical boreholes. By means of the cone, boundaries between various lithological units were detected accurately, the vertical extent of dense and overconsolidated horizons was defined, and thin layers of seasonally frozen sediments and the top boundary of permanently frozen materials were indicated. The temperature profiles obtained from the cone penetration tests were compared with temperature data recorded by the thermistor cables. The maximum dissipation time required to establish accurate soil and water equilibrium temperatures was determined as 900 seconds for the sediments encountered. The maximum discrepancy between thermistor cable and cone temperature data was ±0.2°C. Acoustic wave velocities recorded by the cone were compared with the velocities measured on core samples in the laboratory and with uphole seismic survey results; an excellent correlation was demonstrated. Values of shear strength interpreted from the cone data showed very good agreement with values obtained from the standard penetration tests.

The results of this study show that the acoustic cone penetrometer can provide effective stratigraphic information, and fast and accurate profiles of temperature, acoustic velocities and shear strength of marine sediments even under harsh arctic conditions.

ACKNOWLEDGMENTS

Funding for the field portion of this project was supported by the Office for Energy, Research and Development and the field logistics were provided by the Polar Continental Shelf Project personnel. Contributions made by all the field participants in the 1984, 1985, 1986 and 1987 field drilling and testing programs are gratefully acknowledged. The author is especially grateful to Dr. B.R. Pelletier for his stimulating comments which contributed to the improvement of the paper.

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