39th CGS Conf.
IN-SITU TESTING & Field Behaviour
Ottawa, AUG. 1986

In Situ Testing of Seabottom Sediments, Tuktoyaktuk Area, N.W.T.

R.G. CAMPANELLA
Department of Civil Engineering, University of British Columbia, Vancouver, B.C.
P.J. KURFURST
Terrain Sciences Division, Geological Survey of Canada, Ottawa, Ontario

ABSTRACT

A seismic cone penetrometer and specially equipped testing truck, both developed by the In-Situ Testing Group, Department of Civil Engineering, University of British Columbia (UBC), were used during a two-week experimental program investigating seabottom sediments of the southern Beaufort Sea. Four sites were investigated in detail. At each site one borehole and one to five seismic cone penetration tests were carried out.

The UBC seismic cone measures pore pressure continuously and simultaneously at two locations along the tool, soil temperature and cone penetration verticality, in addition to acoustic velocities, sleeve friction resistance and cone bearing capacity. All measurements, and the soil profile based on their interpretation, are computer plotted and tabulated. Stratigraphic interpretations of these data show good correlations with soil profiles obtained from core logging during drilling. Specific measurements such as temperature and acoustic wave velocities also correlate well with measurements performed on core samples.

Compressional and shear wave velocities were measured at each site at 1 m intervals throughout each profile. The average compressional wave velocity for all soundings ranged from 1600 to 1700 m/s with maximum velocity measured about 2300 m/s. These values correspond well with compressional wave velocities measured on core samples (1400-2370 m/s). The shear wave velocities averaged about 220 m/s; in general these values were lower than values measured on core samples, however.

Representative seismic cone penetrometer test data are presented, detailed comparisons with other field data are made and the performance of the seismic cone penetrometer is evaluated.

The cone penetrometer is found to be a premier geotechnical subsurface profiling tool that provides continuous stratigraphic information with close vertical resolution as well as fast and reliable seismic and temperature data.

INTRODUCTION

As a part of ongoing geotechnical investigations of frozen and unfrozen sediments along proposed pipeline routes, the Geological Survey of Canada (GSC) and the University of British Columbia (UBC) carried out a two-week field experimental program investigating sea- and riverbottom sediments near Tuktoyaktuk, Northwest Territories. Three offshore and one river-crossing sites were investigated in detail. The general map with locations of the study sites is shown in Fig. 1.

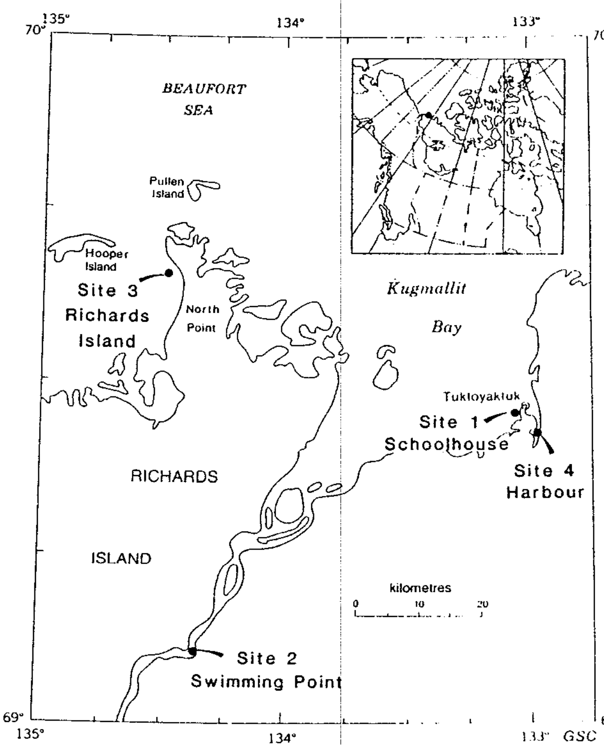


Fig. 1 - Site location map

A seismic cone penetrometer and specially equipped testing truck were used in conjunction with conventional geotechnical drilling and sampling equipment. One borehole and one to five seismic cone penetration tests were carried out at each site. Acoustic wave velocities and temperature measurements were carried out both in situ and on the recovered soil samples. Stratigraphic interpretation, based on core logs and standard laboratory tests (grain size, Atterberg limits, moisture content) of the encountered sediments, was made and then correlated with the data obtained from the seismic cone penetration tests.

A general summary of all work carried out is described in Kurfurst (1986) and Campanella, et al. (1985).

EQUIPMENT AND TECHNIQUES

At each site one borehole and one to five seismic cone penetration tests were carried out. The boreholes were drilled through sea or river ice and water column of as much as 7 m to depths of 13 m to 31 m below seabottom. All boreholes were drilled using an HT-700 hydraulic rotary drill rig. After a 30 cm diameter hole was augered through the ice, the drill rods and the drill bit were lowered to the seabottom and rotated while pumping drilling fluid through the centre of the drill rods and out through the drill bit. When the desired sampling depth was reached, the drill string was pulled back, a Shelby tube sampler was inserted and the sample was taken.

Shelby tube samples were collected from 1.5 m intervals from each borehole. An Aitkins temperature probe was immediately inserted into the bottom of the samples to record their temperature. Samples were then extruded into a split PVC tube, measured, and soil type description and presence of ice, when observed,were recorded. The samples were then photographed, sealed and retained for further detailed logging and testing.

Seismic cone penetration tests were done through holes drilled in ice to the depths ranging from 8 m to 33 m below seabed. Depth of cone penetration was limited by cone refusal caused when either solidly frozen soil or coarse gravel was encountered.

A UBC-developed seismic cone was deployed from a specially equipped truck modified for the arctic environment. A complete description of the in situ testing vehicle and its capability is given in Campanella and Robertson (1981).

The seismic cone penetrometer measures pore pressure continuously and simultaneously at two locations along the tool, soil temperature and cone penetration vertically, in addition to acoustic velocities, sleeve friction resistance and cone bearing capacity. A schematic of the seismic cone used is shown in Fig. 2. The seismic cone penetrometer and its design are described in Campanella and Robertson (1984).

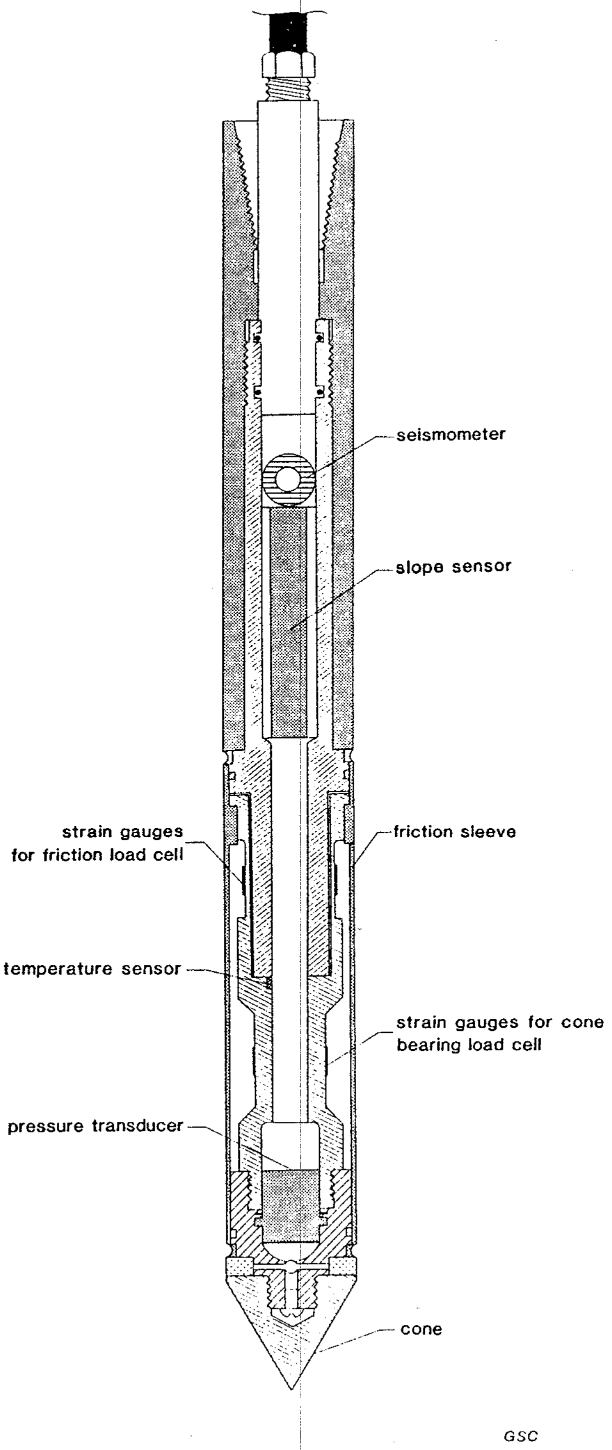


Fig.2 - Seismic cone penetrometer

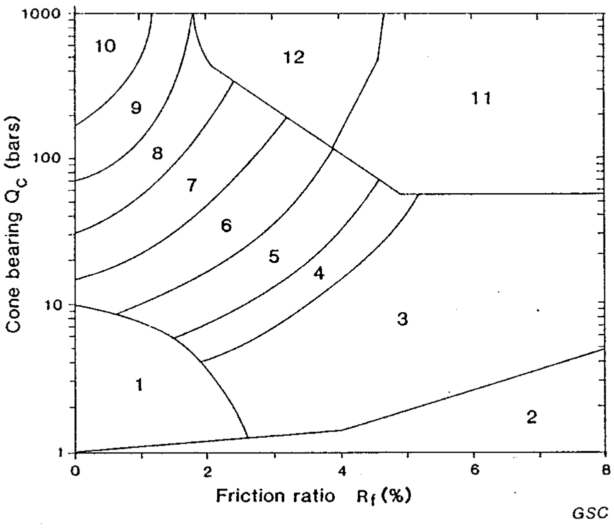
Single and biaxial velocity seismometers (accelerometers) were used to detect the seismic wave traces, generated by surface seismic source. The wave traces were recorded on a digital oscilloscope with floppy disk capability. Explosive caps, detonated at various depths in the water below the ice, were the main seismic source. However, several alternate methods of placing the seismic source into the seabottom were tested, using either a flat blade or a circular plate device. When no water was encountered beneath ice, a polarized seismic signal was generated by striking the rear support pads of the research vehicle with a sledge hammer.

Compressional and shear wave velocities were measured at each site at 1 m intervals throughout each profile. The velocities were also measured in the laboratory on the selected representative core samples recovered during drilling. An OYO Sonic viewer 5217A with two pairs of transmitters and receivers was used to measure first arrivals of the shear and compressional waves independently. Detailed descriptions of the apparatus and the technique used are given by Kurfurst (1977).

FIELD RESULTS

Cone Penetrometer (CPT) Data

The seismic cone penetrometer provides rapid continuous stratigraphic information with close vertical resolution. The stratigraphic interpretation is based on relationship between cone bearing capacity Q_c, and sleeve friction F_s; calculated friction ration R_f is used to categorize soil behaviour types (Fig. 3).



Zone	Q_c/N	Soil behaviour type
1	2	sensitive fine grained
2	1	organic material
3	1	clay
4	1.5	silty clay to clay
5	2	clayey silt to silty clay
6	2.5	sandy silt to clayey silt
7	3	silty sand to sandy silt
8	4	sand to silty sand
9	5	sand
10	6	gravelly sand to sand
11	1	very stiff fine grained (*)
12	2	sand to clayey sand (*)

(*) overconsolidated or cemented

Fig.3 - CPT Soil behaviour type chart

Typically, granular soils have low friction ratios and high cone resistance,while fine grained, cohesive and organic soils have high friction ratios and low cone resistance. Generalized soil profiles, comparable soil profiles from core logging, and plots of generated data for cone sounding test No. 4 at Schoolhouse site are shown in Fig. 4.

All measurements, which also include equivalent relative density (Eq-D_r), equivalent friction angle (Phi), equivalent standard penetration blow count (STP-N), and undrained shear strength (S), were computer plotted and tabulated using a program developed at UBC. A typical computer printout, summarizing data from cone sounding test No. 4, is shown in Table 1.

Seismic Data

Seismic wave velocities were recorded in situ by the accelerometers which are part of the seismic cone penetrometer. The velocities were calculated using a pseudo-time interval technique. The arrival time from source to detector was converted vectorially to a vertical travel path. The difference between successive 1 m depth measurements of vertical travel path time was then used to determine the wave travel time over the 1 m depth interval.

The average compressional (P) wave velocity for all soundings ranged from 1600 to 1700 m/s with maximum velocity recorded about 2300 m/s.

The detection of shear (S) wave velocities was difficult, due to multiple reflection of the P waves off a permafrost boundary at depth or off the sea ice, which masked the S wave arrivals. The shear wave velocities averaged about 220 m/s. Typical example of the compressional and shear wave velocities as recorded by the seismic cone penetrometer is shown in Fig. 5.

Both compressional and shear wave velocities were also measured on the core samples in the laboratory. The compressional wave velocities varied between 1400 and 2370 m/s, while the shear wave velocities ranged from 220 to 360 m/s.

Temperature Data

Typical CPT temperature data, with the comparable temperature measurements made by the temperature probe and those recorded by the thermistor cables,are shown in Fig. 6.

The CPT data represent the temperatures measured in the cone after the soil penetration, using only a short time period for heat dissipation. Typical heat dissipation time averaged about five minutes with a maximum waiting time about 60 minutes. In dense materials a significant amount of heat is generated during cone penetration (4^{o}C at Richards Island site), and accordingly a longer time is required for this heat to dissipate.

Temperatures measured on core samples were recorded with the temperature probe inserted into the sample immediately after its recovery. These temperatures are generally higher than those recorded by the cone, possibly due to thermal disturbance caused by drilling, sample recovery and handling, and because of the time lag between drilling and temperature recording.

Thermistor cables were installed in jet-drilled boreholes at the Richards Island test site in August 1985. Temperatures were recorded immediately after installation and the measurements were repeated periodically to ensure that the readings represent true temperature equilibrium. These temperatures are generally 1 to 2^{o}C

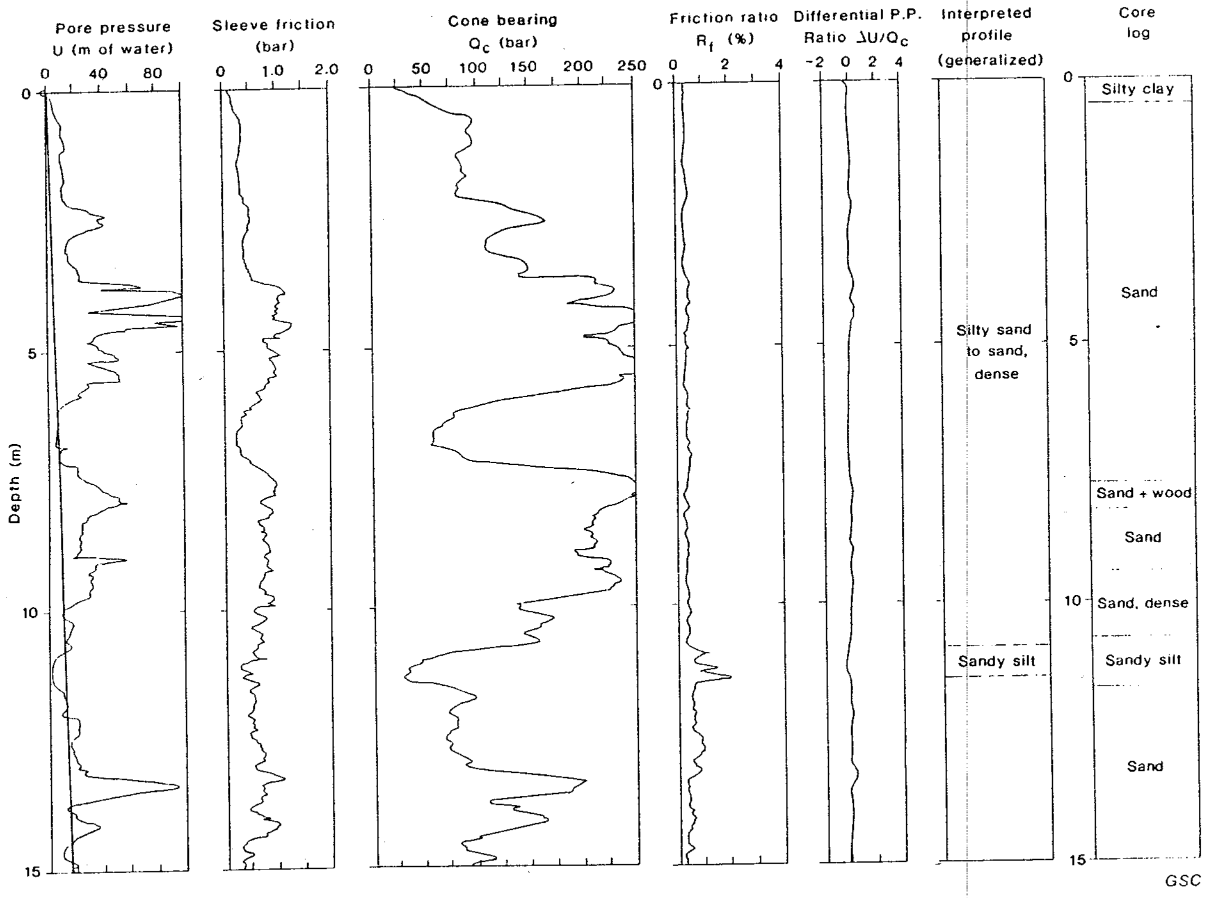


Fig.4 - Data summary - CPT #4

lower than temperatures recorded either by the seismic cone penetrometer or temperature probe.

DISCUSSION

The seismic cone penetrometer test data provided a fast stratigraphic soil profiles in a variety of materials ranging from clays and silts to sands. When compared to the core logs recorded during drilling, no significant differences in stratigraphy were detected. The seismic cone penetrometer defined the boundaries of different lithological units, detected zones of dense, overconsolidated sediments and indicated top boundaries of the frozen sediments. Comparable core logs confirmed the precision of these results. The interpreted undrained shear strength, pore pressure response and seismic data also indicated zones of overconsolidated sediments.

Seismic wave velocity measurements yielded an average value for compressional and shear waves between 1600 and 1700 m/s and 220 m/s respectively with maximum velocities recorded about 2300 m/s and 400 m/s. This compared well with seismic wave velocities measurements on the core samples in the laboratory, which recorded compressional wave velocities between 1400 and 2370 m/s and shear wave velocities between 220 and 360 m/s. Although the range of values of shear wave velocities for core samples compared well with those obtained from CPT, their average values were generally higher.

The temperature measurements recorded by the seismic cone penetrometer during penetration compare favourably with measurements recorded by the temperature probe on the core samples. The results show almost identical trend of the temperature curve but lower values of the absolute temperatures. This difference is considered due to thermal disturbance that the core samples are subjected to during drilling and sample recovery. However, equilibrium temperature measurements recorded by the thermistor cables were 1 to 2°C lower than those recorded by the seismic cone penetrometer, especially in the zone not affected by the seasonal temperature variations. This difference is due to the short CPT recording time during a pause in penetration which did not allow for adequate heat dissipation and for the soil to reach temperature equilibrium.

CONCLUSIONS

The purpose of the study was to evaluate performance of the seismic cone penetrometer under the arctic conditions, to present results obtained and to compare them with results obtained by other conventional methods.

The main conclusions derived from the testing program are:

1. The seismic cone penetrometer is found to be a premier geotechnical subsurface tool that provides continuous stratigraphic information with close vertical resolution, comparable with that provided by conventional drilling.

Table 1 – CPT data

Site : Schoolhouse
CPT No. : GSC No. 4
Comments :425 cm ice + water
Tot. Unit Wt. (avg). : 19 kN/m3

CPT Date : 85/03/23/ 11:00
Cone used : UBC No. 5 face tip

DEPTH (meters)	Q_c (avg) (bar)	F_s(avg) (bar)	R_f(avg) (%)	SIGV' (kPa)	SOIL BEHAVIOUR TYPE	Eq-D_r (%)	PHI deg.	SPT N	S_u kPa
0.25	34.33	0.11	0.32	1.15	silty sand to sandy silt	>90	>48	11	UNDEFINED
0.50	61.26	0.18	0.29	3.44	sand to silty sand	>90	>48	15	UNDEFINED
0.75	91.93	0.28	0.31	5.74	sand	>90	>48	18	UNDEFINED
1.00	95.18	0.31	0.33	8.04	sand	>90	>48	19	UNDEFINED
1.25	96.86	0.30	0.31	10.33	sand	>90	>48	19	UNDEFINED
1.50	85.64	0.26	0.30	12.63	sand	>90	>48	17	UNDEFINED
1.75	89.47	0.27	0.31	14.93	sand	>90	>48	18	UNDEFINED
2.00	87.11	0.30	0.34	17.22	sand	>90	46-48	17	UNDEFINED
2.25	86.99	0.37	0.43	19.52	sand	>90	46-48	17	UNDEFINED
2.50	138.41	0.46	0.33	21.81	sand	>90	>48	28	UNDEFINED
2.75	159.12	0.44	0.28	24.11	sand	>90	>48	32	UNDEFINED
3.00	117.87	0.37	0.31	26.41	sand	>90	46-48	24	UNDEFINED
3.25	111.02	0.36	0,32	28.71	sand	>90	46-48	22	UNDEFINED
3.50	138.40	0.41	0.30	31.00	sand	>90	46-48	28	UNDEFINED
3.75	161.21	0.58	0.36	33.30	sand	>90	46-48	32	UNDEFINED
4.00	224.14	1.05	0.47	35.60	sand	>90	>48	45	UNDEFINED
4.25	212.54	0.99	0.47	37.89	sand	>90	>48	43	UNDEFINED
4.50	246.39	1.02	0.42	40.19	gravelly sand to sand	>90	>48	41	UNDEFINED
4.75	245.17	1.11	0.45	42.49	gravelly sand to sand	>90	>48	41	UNDEFINED
5.00	222.87	0.79	0.35	44.78	gravelly sand to sand	>90	46-48	37	UNDEFINED
5.25	237.82	0.92	0.39	47.08	gravelly sand to sand	>90	46-48	40	UNDEFINED
5.50	257.41	0.95	0.37	49.38	gravelly sand to sand	>90	46-48	43	UNDEFINED
5.75	246.28	0.80	0.32	51.67	gravelly sand to sand	>90	46-48	41	UNDEFINED
6.00	199.73	0.63	0.31	53.97	sand	>90	46-48	40	UNDEFINED
6.25	111.03	0.45	0.40	56.27	sand	80-90	44-46	22	UNDEFINED
6.50	77.08	0.30	0.39	58.56	sand to silty sand	70-80	42-44	19	UNDEFINED
6.75	62.94	0.22	0.35	60.86	sand to silty sand	60-70	40-42	16	UNDEFINED
7.00	63.80	0.26	0.40	63.16	sand to silty sand	60-70	40-42	16	UNDEFINED
7.25	94.76	0.45	0.48	65.45	sand	80-90	42-44	19	UNDEFINED
7.50	185.21	0.79	0.42	67.75	sand	>90	44-46	37	UNDEFINED
7.75	245.63	0.91	0.37	70.05	gravelly sand to sand	>90	46-48	41	UNDEFINED
8.00	252.56	0.73	0.29	72.34	gravelly sand to sand	>90	46-48	42	UNDEFINED
8.25	224.03	0.79	0.35	74.64	gravelly sand to sand	>90	44-46	37	UNDEFINED
8.50	209.44	0.67	0.32	76.94	sand	>90	44-46	42	UNDEFINED
8.75	205.51	0.73	0.36	79.23	sand	>90	44-46	41	UNDEFINED
9.00	204.93	0.75	0.37	81.53	sand	>90	44-46	41	UNDEFINED
9.25	212.20	0.77	0.36	83.83	sand	>90	44-46	42	UNDEFINED
9.50	222.68	0.67	0.30	86.12	gravelly sand to sand	>90	44-46	37	UNDEFINED
9.75	228.58	0.75	0.33	88.42	gravelly sand to sand	>90	44-46	38	UNDEFINED
10.00	173.66	0.69	0.40	90.72	sand	>90	42-44	35	UNDEFINED
10.25	152.61	0.65	0.42	93.01	sand	80-90	42-44	31	UNDEFINED
10.50	156.06	0.58	0.37	95.31	sand	80-90	42-44	31	UNDEFINED
10.75	148.64	0.62	0.41	97.61	sand	80-90	42-44	30	UNDEFINED
11.00	73.16	0.49	0.67	99.90	sand to silty sand	60-70	38-40	18	UNDEFINED
11.25	37.92	0.34	0.90	102.20	silty sand to sandy silt	<40	36-38	13	UNDEFINED

Note: For interpretation purposes the PLOTTED CPT PROFILE should be used with the TABULATED OUTPUT from CPTINTER.

2. The seismic cone penetrometer provides geotechnical data required for detection of dense, overconsolidated sediments in fine grained, unfrozen materials. However, depth of penetration is limited when coarse or solidly frozen materials are encountered.

3. The seismic cone penetrometer records compressional and shear wave velocities needed for calculations of the dynamic moduli of material encountered. The seismic wave velocity measurements compare well with those measured on core samples in the laboratory. Better quality shear wave detection could be achieved by upgrading the electronic filters used to eliminate reflected compressional waves and by improving seismic sources and their location.

4. The seismic cone penetrometer provides good temperature profiles for the tested horizons. The temperature measurements compared well with those measured by the temperature probe on the core samples, but are generally higher than those recorded by thermistor cables. The accuracy of the temperature measurements can be improved if adequate time is allowed for soil to reach its temperature equilibrium after soil penetration.

ACKNOWLEDGMENTS

Support for the field study was provided by the Geological Survey of Canada, Department of Energy, Mines and Resources.

The dedicated work and assistance of A. Brooks, D. Gillespie, J. Greig, G. Jolly, J. Howie, N. Laing and P. Robertson of the Civil Engineering Department, University of British Columbia, and R. Gagne and M. Nixon of Geological Survey of Canada, are much appreciated.

REFERENCES

CAMPANELLA, R.G. and ROBERTSON, P.K. (1981): "Applied cone research"; Symposium on Cone Penetration Testing and Experience, Geotechnical Engineering Division, ASCE, p. 343-362.

CAMPANELLA, R.G. and ROBERTSON, P.K. (1984): "Seismic cone penetrometer to measure engineering properties of soils"; 54th Annual International Meeting and Exposition of the SEG, Atlanta, U.S.A.

CAMPANELLA, R.G. et al. (1985): "Preliminary evaluation of seismic cone penetrometer in Beaufort Sea"; Preliminary report, In-situ Testing Group, Department of Civil Engineering, University of British Columbia, submitted to Geological Survey of Canada.

KURFURST, P.J. (1977); "Acoustic wave velocity apparatus"; Current Research, Part A, GSC Paper 77-1A, p. 73.

KURFURST, P.J. (1986): "Geotechnical investigation of seabottom sediments, Tuktoyaktuk area, District of Mackenzie"; Current Research, Part A, GSC Paper 86-1A, p. 775-778.

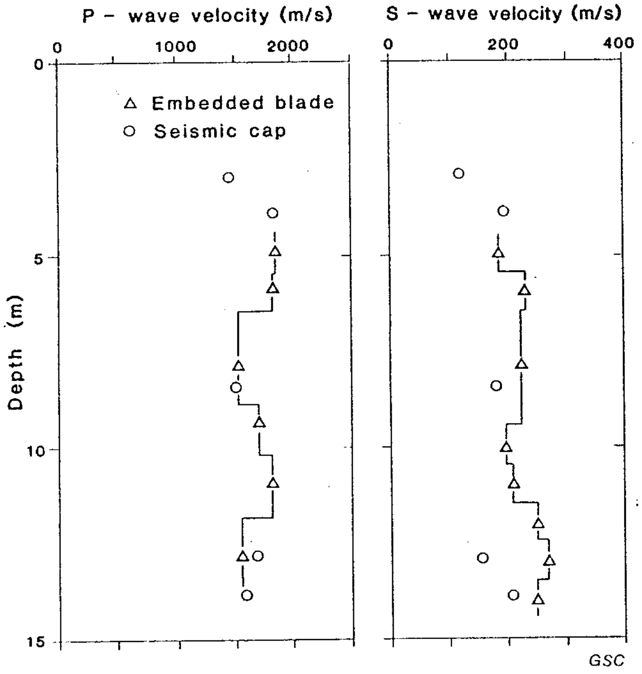


Fig.5 – Calculated seismic velocities – CPT #12

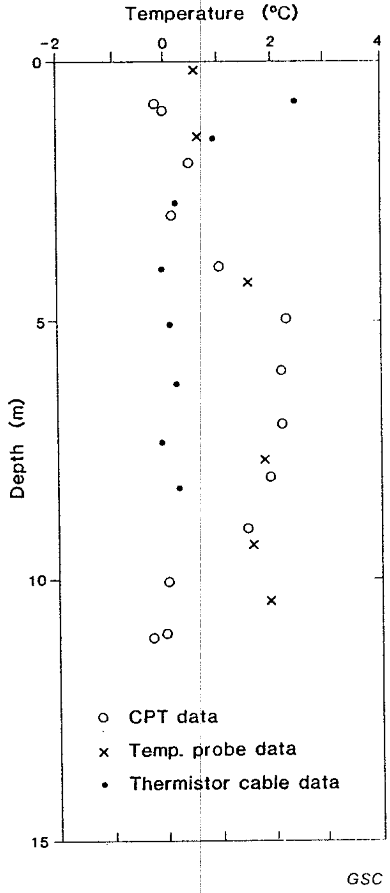


Fig.6 – Temperatures after dissipation – CPT #12