GEOTECHNICAL AND GEOTHERMAL CONDITIONS OF NEAR-SHORE SEDIMENTS, SOUTHERN BEAUFORST SEA, NORTHWEST TERRITORIES, CANADA

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SYNOPSIS Near-shore sediments in the southern Beaufort Sea display high spatial and temporal variability of geotechnical and geothermal conditions. This paper describes results of extensive geotechnical investigations along two diverse transects in frozen and unfrozen near-shore sediments. The geotechnical and geothermal conditions of the near-shore zone are discussed as well as the implications for the design and construction of engineering structures.

INTRODUCTION

Anticipated development of hydrocarbon resources discovered in sedimentary basins underlying the continental shelf of the Beaufort Sea has created a need for detailed knowledge of the geology of the near-shore zone. Data on the geotechnical and geothermal conditions of seabottom sediments are vital to the engineering design of structures such as pipelines and marine terminals. The near-shore zone is an unique environment which typically contains a diverse suite of geological materials undergoing constant modification by active coastal processes. In transgressive margins such as the southern coast of the Beaufort Sea, the near-shore zone can be underlain by several hundreds of metres of perennially frozen sediments which may be in a state of thermal dis-equilibrium.

This paper describes the geological, geotechnical and geothermal conditions of the near-shore sediments occurring off northern Richards Island in the southern Beaufort Sea. The results of detailed geotechnical investigations along two onshore-offshore transects (Figure 1) as well as the scope of techniques used are described in detail.

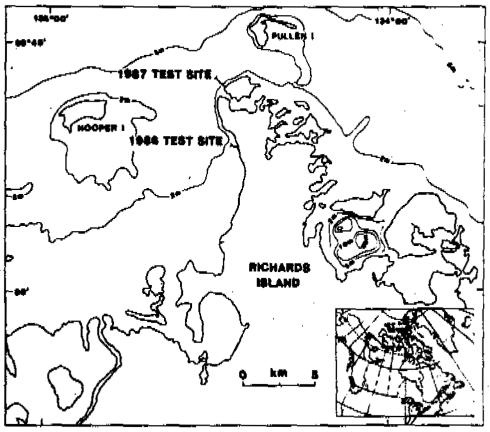

Fig. 1 Site Location Plan

GEOLOGICAL SETTING

Richards Island is underlain by thick deposits of Quaternary sediments which are perennially frozen to several hundred metres depth. Onshore sediments consist of early Wisconsinan and older glacial, fluvial and marine sediments mantled by more recent lacustrine, colluvial and eolian materials of variable thickness (Rampton, in press). Ground ice is commonly present in terrestrial sediments in the form of discrete bodies of massive ice, ice wedges, ice lenses and pore ice (Rampton and Mackay, 1971; Dallimore and Wolfe, this volume).

Coastal areas of the Canadian Beaufort Sea have been experiencing a general marine transgression since at least late Wisconsinan times (Hill et al, 1985). This process has resulted in a typical offshore sequence of marine sediments lying unconformably over older sediments which were once sub-aerially exposed. The near-shore areas have been recently innundated by the sea and therefore represent a transitional zone between the onshore and offshore environments.

The coastline of northern Richards Island exhibits a variety of erosional and accretional landforms. A summary of coastal change in the area since 1947, shown on Figure 2, indicates that retreat rates vary from a maximum of 3.2 m/a to no discernible change. In order to assess the effect of coastal retreat on geotechnical conditions of the near-shore zone, investigations were undertaken at two contrasting sites. The 1986 investigations concentrated on a stable coastal area while the 1987 study site was located in an area experiencing coastal retreat at a rate of about 3 m/a.

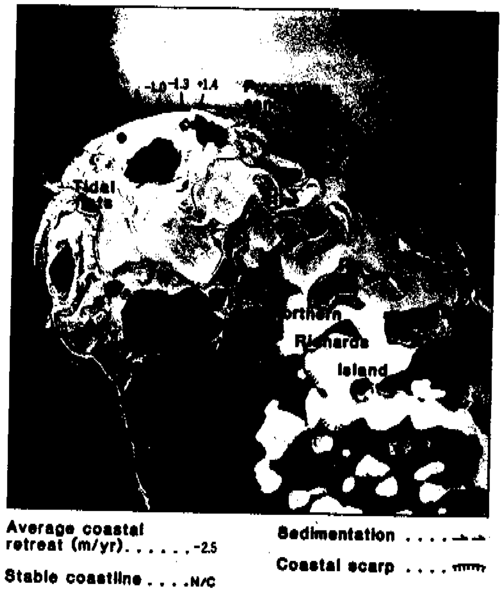

Fig. 2 Aerial Photograph of Northern Richards Island Showing Coastal Change

FIELD INVESTIGATIONS

Eighteen boreholes were drilled along two onshore-offshore transects to depths ranging from 30 m to 40 m. The locations of the drill holes and the transects are shown on Figures 3 to 6. Geotechnical drilling was carried out in the spring using a conventional rotary drill rig capable of collecting 10 cm or 7.5 cm diameter samples. Core samples were collected from all drill holes either continuously or at 1.5 m intervals. After measuring the core temperature with a needle probe, samples were photographed and logged for soil and ice type. All drill holes were cased and then used for seismic and other geophysical logging before thermistor cables were installed (Kurfurst, 1986; 1988). Thermistor cables were monitored until thermal equilibrium was reached after dissipation of disturbance caused by drilling and cable installation.

In addition to the drill holes, 13 cone penetration tests (CPT) were carried out to provide supplementary information. A standard Hogentogler electric cone penetration system and a 10-tonne compression cone were used for the testing. Soil temperatures were also monitored at the cone tip. The location and depth of the CPT soundings are shown on the cross-sections on Figures 3 to 6.

Field work conducted in the summers of 1986 and 1987 documented coastal stratigraphy, ground ice conditions and coastal retreat rates. Installations of supplemental thermistor cables to monitor temperatures at the end of the thaw season were carried out in August of 1985 and 1987 in small diameter jet-drilled holes.

RESULTS

Geological Conditions

The geological and geotechnical conditions of each site have been summarized as simplified cross-sections presented on Figures 3 through 6. Transgressive marine sequences with well defined Holocene unconformities are present at both sites (Figures 3 and 5). Sediments above the unconformity consist of re-worked sands and laminated marine silts. The predominant feature of the very near-shore areas are submerged terrestrial sequences composed of early Wisconsinan fluvial sand and marine silt.

Massive ground ice is common in the terrestrial sediments at the active coastal retreat site where an irregular-shaped ice body was encountered in four boreholes drilled near the coast (Figure 5). Its maximum thickness of more than 10 m was measured in boreholes 87-5. Examination of exposures in the cliff section carried out during the summer, indicates that ground ice in the vicinity of the drill transect has undergone glacial tectonic deformation. Several ground ice bodies exposed near the transect show recumbent folds and brecciated zones with broken ice clasts up to 1 m^2. The irregular shape of the ice body, inferred from borehole information in Figure 5, can be attributed to similar deformation. Sediments exposed in coastal sections in the vicinity of the stable coastal site and frozen terrestrial sediments in near-shore drill holes are generally ice poor (Figure 3).

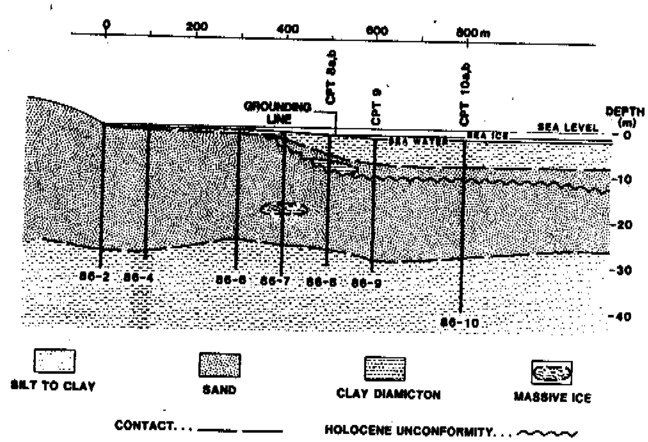

Fig. 3 Geological Cross-section of Stable Coastal Retreat Site

Geothermal Conditions

The geothermal and ground ice conditions at the two sites have been summarized in Figures 4 and 6. The permafrost table (0°C isotherm) at the stable coastal site (Figure 4) occurs close to the surface at the coast and then dips gradually offshore to a depth of more than 8 m below the sea floor at 800 m offshore. At the active coastal retreat site (Figure 6), the permafrost table dips abruptly offshore at 200 m to more than 30 m depth below the sea floor by 1 km offshore. Instrumented drill holes in onshore areas indicate that the mean annual ground surface temperature is approximately -8°C.

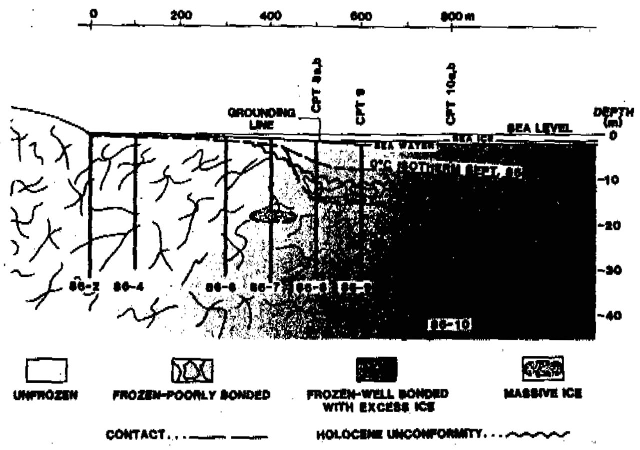

Fig. 4 Geotechnical and Permafrost Cross-section of Stable Coastal Retreat Site

It is apparent that the offshore bathymetry has an important effect on the thermal regime of seabottom sediments at each site. The sea floor at the stable coastal site has a shallow, uniform gradient with an extensive area of sand flats near the shore. During the winter sea water in this area freezes to the bottom, thus allowing cold winter temperatures to penetrate the underlying sediments, maintaining permafrost conditions (Hunter et al, this volume). The active coastal retreat site is characterized by a narrow shelf within 100 m off the coast and then by an abrupt drop in water depth farther offshore. The grounding line of the sea ice is approximately 80 m from the coastline and areas farther offshore experience relatively warm seabottom temperatures that cause deep thaw.

Seabottom temperatures were recorded during the spring 1986 and 1987 drilling programs and during a 5-week period in August and September, 1987. These data indicate that water temperatures at both sites are quite high during the summer with an average temperature range from 8°C to 11°C. However, seabottom temperatures as low as 3.6°C were recorded during short-duration storms. Seabottom temperatures measured during the spring were found to range from -0.2°C to +0.5°C.

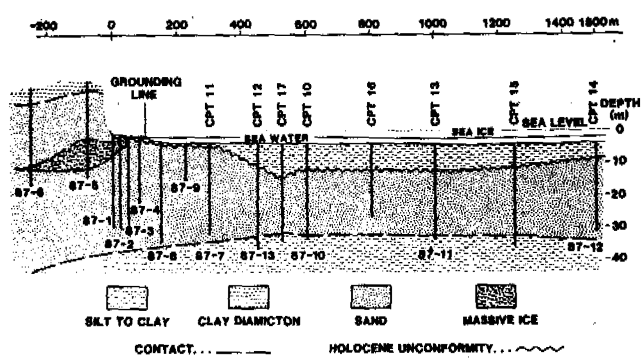

Fig. 5 Geological Cross-section of Active Coastal Retreat Site

The geothermal conditions at the sea bottom contribute to several interesting geological processes. The presence of a seasonally thawing and freezing zone in areas near the shore creates the potential for seasonal frost heave and thaw settlement. At the active coastal retreat site, thaw of buried massive ground ice will result in settlement at the sea floor creating sub-sea thermokarst conditions similar to those described by Mackay (1986). The uneven nature of the Holocene unconformity at the active coastal retreat site between boreholes 87-10 and 87-13 (Figure 5) suggests that some local settlement has occurred but that the depressions at the sea floor have been rapidly infilled by sedimentation.

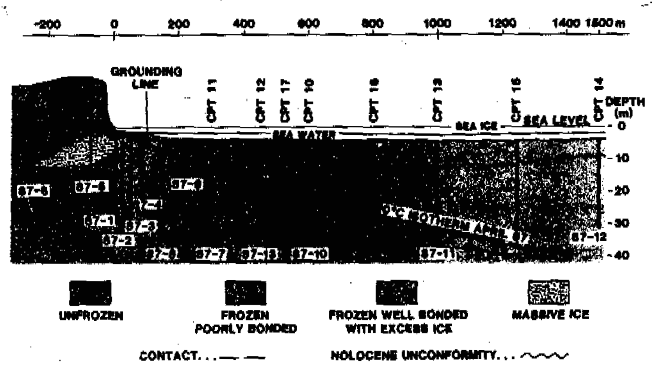

Fig.6 Geotechnical and Permafrost Cross-section of Active Coastal Retreat Site

Geotechnical Conditions

The cone penetrometer (CPT) proved to be an extremely useful complementary tool in determining the strength of unfrozen materials and their insitu geotechnical properties. Temperature data recorded by the cone penetrometer were reliable and consistent with the temperature data measured by the thermistor cables. The cone penetrometer was also useful in accurately delineating the upper limit of frozen ground. An example of typical CPT result is given on Figure 7.

The CPT results indicate a thin discontinuous zone of partially ice-bonded material at the top of the offshore Holocene sediments. As shown on Figure 7, this zone is characterized by high pore water pressure (30 m water column) and increase in sleeve friction and friction ratio just below the mudline. The presence of frozen materials is confirmed by negative temperatures (-0.11°C) recorded by both cone penetrometer and thermistor cable sensors. Both drilling and cone penetration tests indicate that the Holocene sediments present beneath this thin surface layer are relatively soft materials with low bearing capacity of less than 10 bars (Figure 7).

Core logs from drill hole 87-11 and results of CPT 13 (Figure 7) as well as data from other drill holes indicate that the lower parts of the Holocene sediments are slightly overconsolidated. The results of CPT 13 show increases in cone bearing capacity (20 bars),

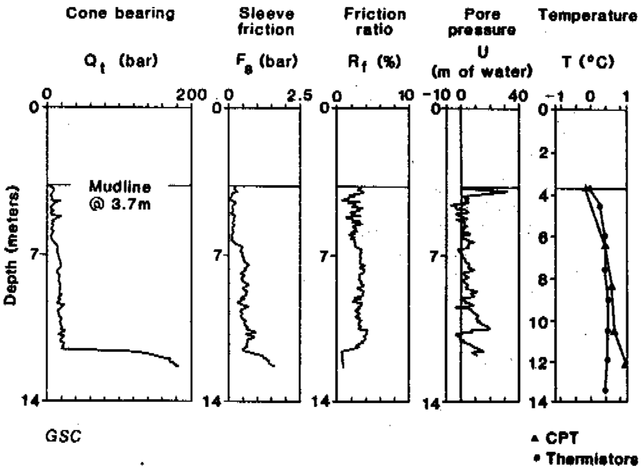

Fig. 7 Cone Penetrometer and Temperature Data for Borehole 87-11 and CPT 13

sleeve friction (0.7 bar) and friction ratio (4%), thus confirming the presence of overconsolidated sediments detected during drilling. Overconsolidation of recent Holocene sediments has also been encountered in areas further offshore (Christian and Morgenstern, 1986). This overconsolidation is likely caused by freeze-thaw effects on the Holocene sediments when they were exposed close to the sea floor. It is also possible that overconsolidation could be caused by cyclic loading by wave action.

The strength of frozen soils encountered below the Holocene sediments was found to be highly variable, especially near the 0°C isotherm. Examination of drill core and limited CPT data indicate a zone of poorly ice-bonded materials in this area. Core collected in this region was easily disturbed by sampling and handling, and varied from supersaturated sand to extremely competent, ice-bonded sand. The thickness of poorly ice-bonded sediments increases with distance from the coastline, as illustrated in Figures 4 and 6. It is assumed that migration of saline pore water affects the freezing point and geotechnical properties of the sediments in this zone. Further work is presently underway to investigate this process and its affects.

DISCUSSION AND IMPLICATIONS FOR ENGINEERING

The investigations carried out to date have indicated that the conditions of near-shore sediments are highly variable in a spatial and temporal sense. Coastal areas which are exposed can undergo high rates of retreat while nearby, more protected areas are relatively stable. The thermal regime of sediments in the near-shore area is also complex. In shallow areas where the sea ice freezes to the bottom during the winter, cold permafrost conditions can be expected. A thick layer of near-surface soil may undergo seasonal cycle of freezing and thawing, resulting in frost heave and thaw settlement. In deeper water (>2m), submerged early Wisconsinan sediments are in a condition of thermal dis-equilibrium which causes their relatively rapid thaw. When sediments are ice rich or contain massive ice, sub-sea thermokarst conditions can occur with substantial thaw settlement. Assuming an average coastal retreat rate of 3 m/a, the thick massive ice body presently exposed below sea level near the active coastal retreat site will be approximately 300 m offshore in 100 years. Assuming a similar sea floor profile as at present, the ice body would then be subjected to rapid thaw. Since this ice body contains over 95 % ice by volume, thawing of the ice will result in up to 10 m of settlement at the sea floor.

These findings have obvious implications for design of engineering structures such as pipelines located in the near-shore zone of the Beaufort Sea and in other permafrost areas with transgressive coastal margins. The highly variable geotechnical conditions of near-shore sediments require that detailed site specific geotechnical investigations are carried out prior to construction. Geotechnical drilling should investigate the properties of both recent marine sediments and of submerged terrestrial sediments. Close attention must also be paid to the present geothermal conditions of the sediments as well as the history of sea floor temperatures to determine if a condition of thermal dis-equilibrium exists. Finally, the temporal variations in coastal position, water depth and sedimentation must be considered at both a site specific and a regional scale.

Geotechnical and geophysical techniques used in the near-shore environment are often quite specialized. Although use of a standard rotary drill rig is recommended, different sampling techniques have to be applied in areas where the sea ice is frozen to the base (CRREL core barrel) then in areas where a water column is present below the sea ice (Shelby tube). The cone penetrometer was found to be a useful tool in this environment, however its penetration is limited to unfrozen and poorly ice-bonded sediments. Several surface and downhole geophysical techniques have been recently tested in the near-shore area and their results are being evaluated.

CONCLUSIONS

Two onshore-offshore transects have been investigated off the coast of Richards Island in the southern Beaufort Sea at a stable coastal retreat site and at an active coastal retreat site. Results of geotechnical drilling, cone penetration tests and thermal studies show that:

1) Near-shore geology is dominated by a wedge of Holocene silt unconformably overlying buried early Wisconsinan sand and silt.

2) Holocene silts occurring near the sea floor are relatively soft materials with low bearing capacities and shear strengths. Zones of slightly overconsolidated Holocene sediments are commonly present at depth.

3) The seabottom temperatures and geothermal regime of the near-shore zone are determined primarily by the offshore bathymetry. Permafrost is preserved in shallow areas close to the shore where the sea ice freezes to the base, thus allowing deep penetration of cold winter temperatures. Areas farther offshore, where the thicker water column maintains warm sea floor temperatures, experience rapid thaw.

4) Sediments near the sea floor are subjected to an annual cycle of freezing and thawing.

5) Thaw of ground ice present in buried early Wisconsinan sediments can result in sub-sea thermokarst conditions.

6) The thickness of poorly ice-bonded early Wisconsinan sediments, possibly resulting from migration of saline pore water, increases with distance from the shore.

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RERERENCES

Christian, H.A. and Morgenstern, N.R. 1986. Compressibility and stress history of Holocene sediments in the Canadian Beaufort Sea. Third Canadian Conference on Marine Geotechnical Engineering, St. John's, NFld, p.275-299.

Dallimore, S.R. and Wolfe, S.A. This volume. Occurrence of massive ground ice in glacial fluvial sediments, Richards Island, N.W.T. Canada. Fifth International Conference on Permafrost, Trondheim, Norway, August 2-5.

Hill, P.R., Mudie, P.J., Moran, K.M. and Blasco, S.M. 1985. A sea-level curve for the Canadian Beaufort Shelf. Canadian Journal of Earth Sciences, Vol 22, p. 1383-1393.

Hunter, J.A.M. et al. This volume. Thermal evidence for an active layer on the seabottom on the Canadian Beaufort Sea shelf. Fifth International Conference on Permafrost, Trondheim, Norway, August 2-5.

Kurfurst, P.J. (compiler) 1986. Geotechnical investigations of the near-shore zone, North Head, Richards Island, N.W.T. Geological Survey of Canada, Open File 1376, 82 p.

Kurfurst, P.J. (compiler) 1988. Geotechnical investigations, northern Richards Island, N.W.T. -Spring 1987. Geological Survey of Canada, Open File 1707, 147 p.

Mackay, J.R. 1986. Fifty years (1935 to 1985) of coastal retreat west of Tuktoyaktuk, District of Mackenzie. Geological Survey of Canada, Paper 86-1a, p. 727-735.

Rampton, V.N. In press. Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories. Geological Survey of Canada, Memoir 423.

Rampton, V.N. and Mackay, J.R. 1971. Massive ice and icy sediments throughout the Tuktoyaktuk Peninsula, Richards Island and nearby areas, District of Mackenzie. Geological Survey of Canada, Paper 71-21, 16p.

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