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Geotechnical Characteristics of Bottom Sediment in the Northern Bering Sea

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Abstract

Yukon sediment of Holocene age, consisting dominantly of silty fine sand and sandy silt, covers the bottom of central and western Norton Sound, which is a high energy environment involving extensive ice loading, high waves, and strong bottom currents. The sediment contains significant amounts of sand in some areas and a generally minor amount of clay-size material ranging from 0 to 20 percent. Moreover, it is generally dense although loose and weak zones occur at the surface and also at depth between relatively dense layers. These characteristics, evidence of storm sand layers and scour depressions, and the results of preliminary analytical studies indicate this sediment is susceptible to liquefaction during major storms.

Substantially finer grained, weak, and highly compressible sediment of Holocene age, derived from the Yukon River and from local rivers and streams, covers eastern Norton Sound and the Port Clarence embayment, which are low

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energy environments with negligible ice loading, low waves, and weak bottom currents.

Transgressive deposits of late-Pleistocene age that cover the bottom of Chirikov Basin include an inner-shelf fine sand underlain by a basal transgressive medium sand that is exposed on the north and east flanks of the basin. Geotechnical data on the latter, obtained in the sand-wave fields near Port Clarence, show the material is loose near the surface but becomes firm rapidly with depth and could not be penetrated more than about 3 m with the Alpine vibratory sampler.

Pleistocene peaty deposits underlie the Holocene and late Pleistocene deposits in both Norton Sound and Chirikov Basin and are somewhat overconsolidated, probably because of subaerial desiccation during low sea level stands in the late Pleistocene. These materials have a higher clay content than the overlying deposits and they contain substantial amounts of organic carbon and gas. The presence of gas suggests that in situ pore pressures may be high. If so, the strength of the material could be low even though the material is generally overconsolidated.

Introduction

During the last few years the U.S. Geological Survey (USGS) has been acquiring geotechnical data on bottom sediment in the Northern Bering Sea. This effort has been part of a broad group of USGS studies in this region aimed at clarifying and evaluating those geologic conditions and processes that may be hazardous to offshore resource development activities (Thor and Nelson, 1979; Larsen, Nelson, and Thor, 1980).

Previous reports concerning this geotechnical effort include the papers by Clukey, Nelson, and Newby (1978); Nelson, Kvenvolden, and Clukey (1978); Nelson et al. (1979); and Sangrey et al. (1979). These reports describe near-surface data on samples obtained during 1976 and 1977 with box corers, Soutar Van Veen samplers, and a Kiel vibracore sampler capable of penetrating 2 m beneath the ocean floor[3]. The data also include penetration rate measurements during vibracorer sampling operations. During 1978, additional samples and penetration records were obtained with an Alpine vibratory corer system equipped to obtain 8.89 cm diameter continuous samples to a maximum depth of 6 m. All of the data obtained to date have been compiled for the Bureau of Land Management in a USGS open-file report by Larsen, B. R., et al. (1980).

The purpose of this paper is to summarize the geotechnical information obtained in the above studies in relation to the geologic and environmental conditions in the northern Bering Sea and to assess the implications of these data with regard to potential hazards to offshore resource development activities in the region.

Geologic and environmental framework

The bottom of Norton Sound consists of silty fine sand and sandy silt of Holocene age discharged from the Yukon River, except for nearshore areas where Pleistocene (>10,000 years B.P.; Hopkins, 1975) transgressive deposits remain and tidally scoured troughs where transgressive and Holocene deposits are mixed (Fig. 1; Nelson, this volume, Fig. 6). In southern Norton Sound, the Holocene sediment is interbedded with fine sand layers as much as 20 cm thick near the Yukon Delta. Pleistocene freshwater silt interbedded with peaty muds and peat layers underlies the Holocene sediment.

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[3] Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Most of Chirikov Basin is covered by an inner shelf fine sand deposited by the late Pleistocene shoreline transgression across this region (Fig. 1; Nelson, this volume, Fig. 6). This deposit is underlain by a basal transgressive medium sand that is exposed on the north and east flanks of the basin. Lag gravels are exposed near the basin margins where the late Pleistocene shoreline transgression has reworked pre-Quaternary bedrock and glacial moraines and where strong modern currents have prevented subsequent deposition. Strong bottom currents and water circulation patterns have inhibited deposition of Holocene sediment from the Yukon River throughout Chirikov Basin, except for some accumulations with ice-rafted pebbles in local depressions in eastern and southern Chirikov Basin (McManus, Hopkins, and Nelson, 1977).

Prior to the deposition of the transgressive sand layers, tundra-derived peat deposits formed during several Pleistocene low sea-level stands that periodically exposed the entire northern Bering shelf until 12,000-13,000 years ago. These Pleistocene limnic peaty muds generally overlie Pleistocene glacial and alluvial deposits that are underlain by pre-Quaternary bedrock.

The Pleistocene peaty mud is a source of biogenic gas throughout the region. Seismic profiles showing acoustic anomalies associated with these materials indicate gas concentrations are of sufficient magnitude to affect sound transmission throughout Norton Sound (Holmes and Thor, this volume). The presence of shallow craters in the thin Holocene sediment in east-central Norton Sound suggests venting of biogenic gas accumulations from the underlying peaty muds. Generally low background levels of dissolved hydrocarbons in the waters of Norton Sound and high gas contents in the underlying peaty mud suggest venting is episodic, while the Holocene sediment generally acts as a seal preventing the biogenic gas from diffusing freely to the sea floor as it appears to do through the transgressive sand in Chirikov Basin (Nelson et al. , 1979).

A large submarine seepage of thermogenic gas in west-central Norton Sound was discovered in 1976 (Cline and Holmes, 1977; Kvenvolden et al., 1979b). Acoustic investigations indicate the presence of bubble-phase gas associated with the sediment in the seep in an area of 50 km^2 (Nelson et al., 1978). Detailed geophysical and geochemical studies indicate that hydrocarbons and CO_2 are migrating upward along a major growth fault in the sedimentary section (Kvenvolden et al., 1579a).

Bottom sediment in the northern Bering Sea is exposed to ice loading, cyclic stress from waves, and drag from bottom currents (Table 1). Ice loading is extensive in the vicinity of the Yukon Delta (Thor and Nelson, 1979). High waves and strong bottom currents occur in central and western Norton Sound and in Chirikov Basin. Storm waves and bottom currents cause significant reworking and erosion of the sediment in Norton Sound (Larsen, Nelson, and Thor, 19: 9) and also cause the transport of sediment from Norton Sound to the Chukchi Sea, almost 1000 km to the northwest (Cacchione, Drake, and Weiberg, this vo ume; Dupré and Thompson, 1979; Nelson and Creager, 1977; Drake et al., 1980). Two areas in this study, Port Clarence and eastern Norton Sound, are protected from large waves and strong bottom currents.

Geotechnical profiles

Methods

The geotechnical profiles (Figs. 2-6) present, for each of the regions outlined in Table 1, information concerning the composition and the relative density or consolidation state of the materials. Direct evidence concerning the composition of the materials includes the data on lithology, texture, Atterberg limits, and gas content. The other data on moisture content, density, strength indices, and vibracore penetration resistance reflect the combined influences of the composition and the relative density or consolidation state. The latter can usually be inferred on a qualitative basis from the suites of information presented.

The data in Figs. 2-6 were obtained with shipboard and laboratory procedures as follows: penetration rates were derived from vibratory corer penetration rates during sampling; gas content data were obtained on shipboard from 10- to 15-cm sample tube sections using the procedures described by Kvenvolden et al. (1979a); bulk densities of tube sections were calculated from shipboard measurements of their volume and weight; visual descriptions, shear strength index measurements, and subsamples for moisture content, density, Atterberg limits, and texture analyses were obtained on shipboard from split tube sections of all cores except 78-1 through 78-5. The latter cores were preserved on shipboard and were subsequently extruded, logged, and tested in the USGS geotechnical laboratory in Denver. The Holocene-Pleistocene boundaries noted on Figs. 2-6 were derived from lithologic logging and radiocarbon dates (Nelson, this volume), and from microfaunal analyses (McDougal 1, this volume). Texture analyses were run with gee' ogic (Larsen, B. R., et al., 1980), and engineering standard (Amer can Society for Testing and Materials, 1977) sieving and sedimentation column techniques. Moisture content and density data were obtained on subsamples taken with the miniature coring device described by Clukey et al. (1978). Atterberg limits were run in accordance with ASTM Standards using the wet preparation method, D 2217 (American Society for Testing and Materials, 1977). Strength index data were obtained with laboratory vane, hand vane, pocket penetrometer, and unconfined compression test equipment. Circumstances did not generally allow these measurements to be made under controlled conditions with standardized procedures that must be employed for the data to have quantitative significance regarding shear strengths. Nevertheless, these data show differences in strength that reflect variations in the composition and the relative density or consolidation states of the materials tested. The absence of strength index data in some of the profiles is also significant in that materials, such as clean sands that do not possess any apparent cohesion, cannot be tested with the strength index test methods used in this study.

Yukon Prodelta

The three profiles in the vicinity of the Yukon Delta (Fig. 2) show mostly Holocene materials that are dominantly silty fine sand, and sandy silt with occasional thin beds of organic clayey silt having clay contents generally less than 20 percent. Gas contents vary over a wide range at station 78-22 from about 0.2 to 70 ml/1 of interstitial water; the range at stations 78-23 and 78-24 is considerably less, from about 0.8 to 4.0 ml/1. The relative density of the material varies over a wide range. Moderately dense to dense zones predominate. However, loose zones, indicated by a watery appearance and very low strengths, are particularly evident at a depth of 2-3 m at station 78-22, and from the surface to a depth of about 1.5 m at station 78-24. The watery appearance of the loose zones emerged fairly rapidly after the core was split, apparently because the material densified in response to vibrations generated by the ship engines. The variations of penetration resistance with depth generally correlate with the presence of loose or dense zones. The variations in gas content with depth do not show a close association either with relative density as inferred above or with the variations in texture, density, and strength with depth.

West-central Norton Sound

The five profiles in west-central Norton Sound (Fig. 3) are located in the thermogenic (Kvenvolden et al. , 1979a) gas seep acoustic anomaly (stations 78-1, 78-2, and 78-3), within a nearby biogenic (Kvenvolden et al., 1979a) gas acoustic anomaly (station 78-4), and-adjacent to the biogenic gas acoustic anomaly (station 78-5). Very high gas contents occur at one location in the thermogenic anomaly (station 78-3) and in the biogenic anomaly (station 78-4). Much lower gas contents occur at stations 78-1 and 78-2 in the thermogenic anomaly and at station 78-5 adjacent to the biogenic anomaly. These profiles penetrate silty fine sand and sandy silt that are similar to the materials in the Yukon Delta region (Fig. 2) and that are probably Holocene deposits because of their lithology, texture, and consistently low moisture contents. The two profiles with very high gas contents also penetrate Pleistocene peaty muds at depths of about 3 m and 1 m at stations 78-3 and 78-4, respectively. Note that the high water contents and low densities are clearly associated with the peaty muds. The relative density of the materials varies over a wide range, which is similar to the range observed in the Yukon Delta region (Fig. 2) as indicated by watery-appearing zones and the wide variations in strength. The vibracore penetration resistance appears to correlate in general with the strength data, although not below 3 m depth at station 78-4. Low penetration resistance is associated with very high gas contents in the profile at station 78-3 and above 3 m in the profile at station 78-4. However, the increase in penetration resistance below 3 m at station 78-4, and the low penetration resistance at station 78-5 are not associated with changes in, or high values of, gas contents, respectively.

East-central Norton Sound

In east-central Norton Sound (Fig. 4) four of the five profiles (stations 78-6, 78-9, 76-121, 76-125) penetrate thin deposits of Holocene silty fine sand and sandy silt and extend into the underlying Pleistocene deposits which include freshwater peaty mud. The profile at station 78-10 appears to penetrate only the Holocene material. Compared with the west-central Norton Sound and Yukon Delta regions (Figs. 2 and 3), these profiles show similar materials with relative densities that are low near the surface, but that increase much more rapidly with depth. In fact, the Alpine vibratory corer was unable to penetrate deeper than about 3 m in this region. The rapid increase in penetration resistance with depth occurs in both Holocene and Pleistocene materials, even though their gas contents are similar to those in weaker materials at other locations such as in the station 78-5 profile in west-central Norton Sound (Fig. 3).

Eastern Norton Sound and the Port Clarence embayment

The profiles from eastern Norton Sound, near Stuart Island, and from the Port Clarence embayment (Fig. 5) penetrate materials that are generally finer grained and have relatively high moisture contents, high plasticity, low density, low strength, and low penetration resistance compared with the materials in the regions previously discussed. The characteristics of these profiles (Fig. 5) appear to be associated with their low-energy environments. Station 78-21 is located in Port Clarence, the most protected environment in the region. The materials in this profile have substantially higher water contents (∿90 percent) and lower strengths (∿10 kPa) than other materials encountered in the northern Bering Sea. The very low strengths and their uniformity with depth suggest the Holocene materials in Port Clarence may be somewhat underconsolidated; i.e., not yet in equilibrium with the weight of the material.

Sand-wave fields near Port Clarence

Four profiles in the sand-wave fields near Port Clarence in the Chirikov Basin are shown in Fig. 6. Stations 78-14 and 78-16 are located on one sand-wave crest, and the profiles penetrate medium sand that appears to be the basal transgressive deposit described by Nelson (this volume, Fig. 6). Station 78-15 is located in the adjacent sand-wave trough to the east, and penetrates the Pleistocene peaty mud that underlies the basal transgressive deposits in the region. The profile at station 78-17 is located on the adjacent sand-wave crest to the east. It penetrates the basal transgressive sand to a depth of about 1.5 m and the Pleistocene peaty mud from 1.5 to 2.2 m. The materials from 2.5 to 3.5 m are poorly to moderately sorted medium to fine sand with abundant pebbles and some silt- and clay-sized material. Below a sharp contact at 3.5 m the material appears to be glacial till consisting of a firm muddy sand with scattered pebbles.

The relative density of the basal transgressive sand is low near the surface but increases rapidly with depth, as indicated by the strength and penetration resistance data in the profiles for stations 78-14 and 78-16. The peaty mud at stations 78-15 and 78-17 is comparatively weak and has a very wide range of water contents due to the intermittent distribution and variable character of the peaty material. At station 78-17 the sand beneath the peaty mud appear to be firm and dense with a moderate to high resistance to vibracore penetration.

Consolidation and static triaxial data

Consolidation data (Fig. 7) on three box core samples of Holocene sediment show a wide range in the initial void ratio and compressibility of materials from the Yukon Delta and central regions of Norton Sound (Fig. 1; stations 76-154, 76-156). The wide range in these properties is consistent with the high variability in the strength and penetration resistance of these materials as shown in Figs. 2, 3, and 4. The compressibilities of the samples from station 76-156 may be high compared with other materials in these regions, because this station is located near vibracore station 78-24, whose profile (Fig. 2) shows a very loose and weak zone at the surface.

Triaxial data on vibracore samples of Holocene Yukon sediment from stations 78-22 and 78-23 (Fig. 8) show moderate to high static strengths with friction angles in the range of 35° to 40°. The variation in friction angle is small for the samples from station 78-22, consistent with the small variations in texture and density among the samples. The wider variation in friction angle for the samples fran station 78-23 appears to be associated with variations in both the texture and density of the samples tested.

Soils that tend to contract during shear (contractile) weaken and may liquefy during cyclic loading from earthquakes and ocean waves (Sangrey, et al., 1978). The stress paths in Fig. 8 show the materials tested are generally contractile at low deviator stress levels and become dilative (tend to dilate during shear) as they approach the yield surface. Moreover, with the exception of the sample from 2.34 m depth at station 78-22, the stress paths become less contractile and more dilative at decreasing initial volumetric stress levels. This behavior pattern is normal for homogeneous material. The in situ stresses at the depths fran which the samples were obtained are on the order of 10 kPa to 30 kPa. These stresses are very low compared to the initial volumetric stresses used to obtain the data in Fig. 8. Therefore, the behavior of the materials in situ should be less contractile and more dilative than that shown by the stress paths in Fig. 8.

The stress path for the sample from 2.34 m depth at station 78-22 (Fig. 8) is of particular interest in that it shows this sample is more contractile at low stress levels than any of the samples tested. This behavior is consistent with the data in Fig. 2 which shows this sample represents the loosest zone in the profiles at stations 78-22 and 78-23. Thus the data indicate that loose zones within the Holocene Yukon sediment are of the most concern with regard to strength loss and liquefaction during cyclic loading from earthquakes and ocean waves. Work in progress is aimed at defining the potential for strength loss in these materials on a more quantitative basis (Clukey, Cacchione, and Nelson, 1980).

Discussion of potential hazards

Potential hazards associated with the geotechnical characteristics of bottom sediment in the northern Bering Sea include the liquefaction of bottom sediments in response to ocean waves, earthquakes, and the upward migration of gas from thermogenic and biogenic sources; the scour and transport of bottom sediments and mobile bed forms in response to bottom currents; low strength and high compressibility of materials in low relative density and consolidation states; and gas-charged sediment.

Liquefaction is of particular concern in central and western Norton Sound because the area is exposed to strong cyclic loading from stern waves and is underlain by gas-charged material. Moreover, the susceptibility of the Holocene Yukon sediment in these regions to liquefaction is suggested by its dominantly silty fine sand and sandy silt texture and by the occurrence of relatively loose zones within it (Figs. 2, 3, 4). In addition, historic occurrences of wave-induced liquefaction are suggested by evidence of widespread storm-sand layers and scour depressions in the vicinity of the Yukon Delta (Nelson this volume; Larsen et al., 1979).

Work in progress is aimed at assessing on a quantitative basis the susceptibility of the Holocene Yukon sediment to liquefaction during storm waves. The approach involves the measurement of stern waves to define the cyclic bottom stresses induced during major storms; laboratory cyclic shear tests on Yukon Prodelta materials to determine the dynamic properties that govern the rate of pore pressure increase and associated degradation of strength during cyclic loading; and analyses of these measurements with a finite-element model that takes into account both the buildup of pore pressure induced by cyclic loading and the concomitant dissipation of pore pressure that is governed by the permeability of the material.

Preliminary analyses have been completed (Clukey et al., 1980) for a semi-infinite half-space model of the Yukon prodelta using dynamic property and permeability data estimated from the geotechnical characteristics reported in this paper together with 3-m and 6-m sinusoidal surface waves. The 3-m wave represents worst-case conditions for a storm recorded in July 1977, and the 6-m wave corresponds to a l-percent occurrence interval for storms in September and October (Arctic Environmental Information and Data Center, 1977). The results indicate the prodelta will not liquefy in response to the 3-m storm wave even for the extreme case when zero dissipation of pore pressure is assumed. However, the results for the 6-II stem wave, presented in Fig. 9, indicate the sediment will liquefy to a depth of approximately 3.5 m. The results in Fig. 9 further indicate that the depth of liquefaction varies with storm duration but does not increase significantly for durations greater than 1 hour. This relation is suggested by the 4-m pore pressure contour, which is increasing at a very slow rate at the end of the l-hour stem assumed in the analysis.

Materials with low strength and high compressibility are present in eastern Norton Sound and the Port Clarence embayment. Comparison of Fig. 5 with Figs. 2, 3, and 4 shows that these materials are substantially finer grained and weaker than those in central and western Norton Sound. Because eastern Norton Sound and the Port Clarence embayment are protected from strong bottom currents and large waves, deposition has taken place in a low energy environment. Also the materials have not been subjected to cyclic shear stresses associated with large waves, which have probably densified much of the sediment in other parts of the northern Bering Sea. The organic sandy clayey silt in the Port Clarence embayment is particularly weak and highly compressible because the very low strengths indicate the material may be somewhat underconsolidated.

Scour and transport of bottom sediment depend on the drag associated with bottom currents and the strength of the bottom sediment. Bottom currents are strong in central and western Norton Sound (Table 1). The bottom sediment is loose and weak at some locations in these regions (Figs. 2, 3, 4) and also in the sand waves near Port Clarence in Chirikov Basin (Fig. 6). In addition, the bottom sediment in central and western Norton Sound appear to be susceptible to liquefaction during major storms. These conditions are consistent with evidence of scour depressions in the vicinity of the Yukon Delta and also evidence for the large-scale transport and modification of sand waves near Port Clarence in the Chirikov Basin (Nelson, this volume; Larsen et al., 1979; Larsen et al., 1980).

The importance of gas in sediment depends on whether it is present in the bubble phase and whether the amount present is sufficient to cause significantly elevated pore fluid pressures. Elevated pore pressures can induce liquefaction in overlying materials, and they are associated with reductions in the strength of sediment in situ (Sangrey, 1977).

Seismic and core studies in Norton Sound suggest bubble phase gas is present in the anomaly associated with the thermogenic gas seep south of Nome and at several other locations where biogenic gas is being generated in the Pleistocene peaty mud beneath the Holocene silt (Kvenvolden et al., 1979a;

Holmes and Thor this volume; Kvenvolden et al., 1980; Nelson et al., 1978; Nelson et al., 1979).

Previous work that suggests bubble phase gas may be causing elevated pore pressures in situ includes: limited data showing an association of low vibracore sample penetration resistance with very high gas contents (Nelson et al., 1978); and studies of shallow craters on the bottom of east-central Norton Sound which attribute their origin to episodic venting of biogenic gas generated in the Pleistocene peaty mud and trapped by the overlying Holocene Yukon sediment (Nelson et al., 1979).

The geotechnical profiles in this paper (Figs. 2-6) show additional data concerning the association of vibracore penetration resistance and gas contents. Low penetration resistance is associated with very high gas contents in some of the profiles (see stations 78-3, 78-4, 78-8, and 78-15), but not in general as noted in the section on geotechnical profiles a'hove. For example, the penetration resistance at station 78-5 is about the same as that at station 78-3 even though the gas contents in the two profiles differ substantially.

However, the lack of consistent correlations between gas content and penetration resistance in all the profiles does not eliminate the possibility that gas is causing elevated pore pressures in situ. The relative density or consolidation state of the materials also influences the penetration resistance and may be masking the effects of gas. In this regard the association of the shear strength and penetration resistance data in the profiles is of interest because both measurements are influenced by the relative density or consolidation state, but only the penetration resistance is influenced by in situ elevated pore pressures. The strength data were obtained from samples on shipboard and in the laboratory where elevated pore pressures would have easily dissipated prior to the measurements.

The importance of the relative density or consolidation state of the material on penetration resistance is clearly evident in the geotechnical profiles from eastern Norton Sound and the Port Clarence embayment (Fig. 5). As noted in the discussion above very low strengths occur because these locations are not exposed to significant ice loading and waves that can densify and consolidate sediment. The penetration resistance is correspondingly low, it varies with the shear strength, and it does not appear to be influenced by variations in gas content. Similarly, in the profiles from the Yukon Delta region (Fig. 2), the penetration resistance is more closely associated with relative density, as indicated by the strength data, than with the gas content.

Hence the question remains whether significant elevated pore pressures associated with biogenic and thermogenic gas exist in the bottom sediment of the northern Bering Sea. Additional work is needed to determine the magnitudes of in situ pore pressures and their regional distribution.

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Figure Captions

1. Location map of northern Bering Sea showing regions and sampling stations cited in this paper.
2. Geotechnical profiles from the Yukon Prodelta.
3. Geotechnical profiles from west-central Norton Sound. Stations 78-1, 78-2, and 78-3 are in the thermogenic gas seep acoustic anomaly south of Nome. Station 78-4 is on a nearby biogenic gas acoustic anomaly. Station 78-5 is adjacent to the biogenic gas acoustic anomaly.
4. Geotechnical profiles from east-central Norton Sound where shallow gas craters are associated with thin deposits of Holocene Yukon silt overlying Pleistocene freshwater peaty mud.
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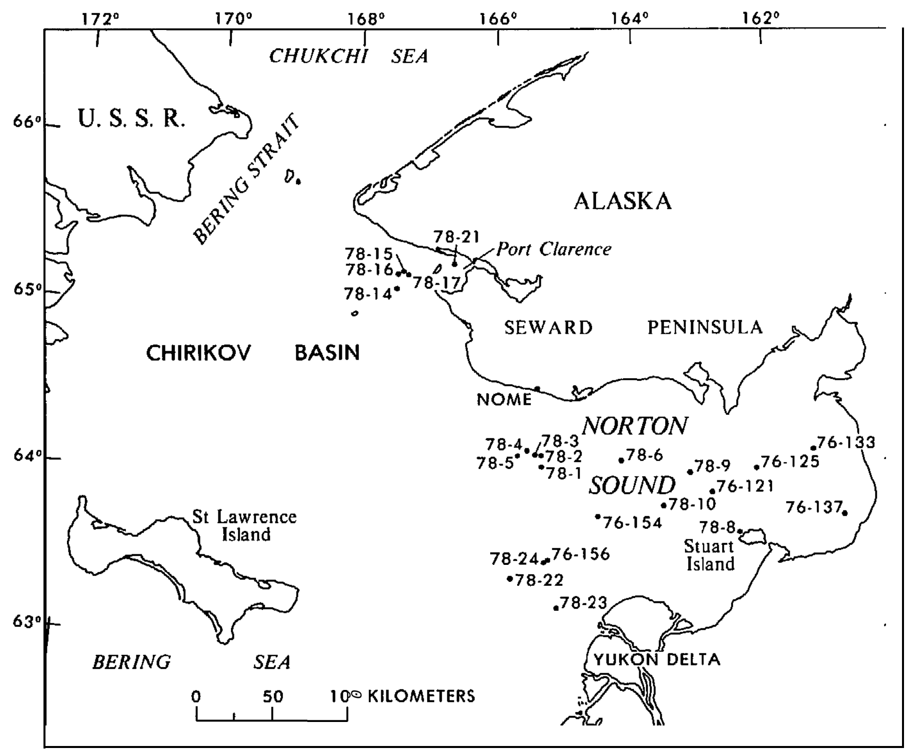
6. Geotechnical profiles from the sand-wave fields near Port Clarence in the Chirikov Basin. Stations 78-14 and 78-16 are located on one sand-wave crest Station 78-17 is located on the adjacent sand-wave crest. Station 78-15 is in the trough between these sand-wave crests.
7. Consolidation data on samples of Holocene Yukon silt from box cores in the vicinity of the Yukon Delta and central Norton Sound. (See Fig. 1.) Box core station 78-156 is adjacent to vibracore station 78-24 whose geotechnical profile is shown in Fig. 2. ω = moisture content in percent dry soil weight; γ_t = bulk density in g/cm3; C_c = compression index. Tests run according to procedures described by the American Society for Testing and Materials (1977) and Wissa et al. (1971).

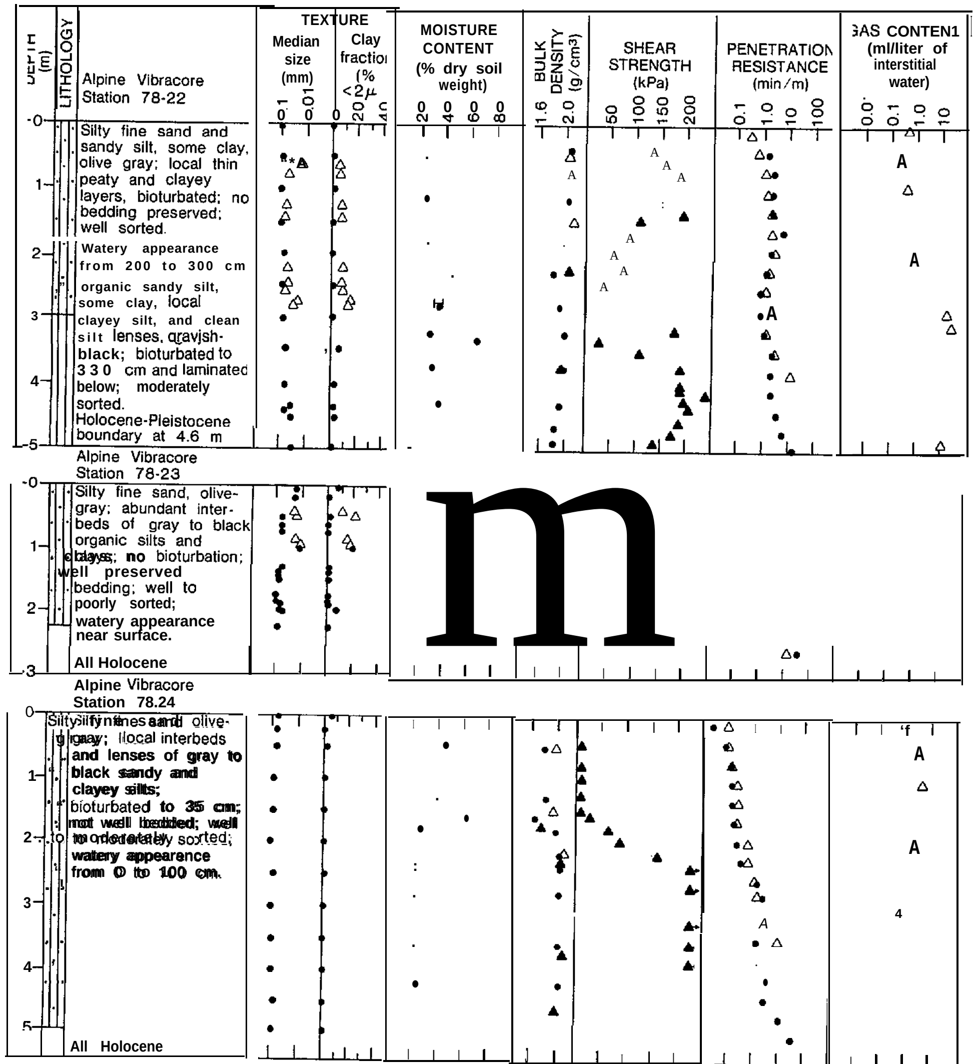
8. Consolidated-undrained triaxial data on samples of Holocene Yukon silt from Alpine vibracores at stations 78-22 and 78-23 near the Yukon prodelta (see Fig. 2). ϕ' = effective friction angle. σ_1 and σ_3 are the total vertical and horizontal stresses, respectively. σ_1' and σ_3' are the effective vertical and horizontal stresses, respectively. ω and γ_t are defined in the caption for Fig. 7. d_{50} and $<2\mu$ are the median grain size and minus 2 micron fraction, respectively. Tests run according to procedures described by Bishop and Henkel (1962).

9. Results of preliminary analyses of wave-induced liquefaction potential of Holocene Yukon silt near the Yukon prodelta, assuming a wave height of 6 m, a period of 10 seconds, a relative density of 54 percent, and a coefficient of permeability of 1.50×10^{-6} cm/s. U/σ = ratio of pore pressure to total overburden stress. The figure shows the variation of pore pressure ratio with time at depths below the sediment surface ranging from 0.25 m to 6 m.

Region	Geologic units	Origin	Gas	Environmental Loading		
				Waves	Bottom currents	Ice
Yukon prodelta.	Holocene silty fine sand and sandy silt with interbedded storm sand layers less than 20 m thick.	Yukon River. High energy deposition and redeposition.	Biogenic	High	Strong	Extensive
West-central Norton Sound.	Holocene silty fine sand and sandy silt, bioturbated, 1-2 m thick, over	Yukon River. Medium energy deposition,	Thermogenic and biogenic	Medium to strong	Medium to strong	Low
	Pleistocene freshwater peaty mud.	Freshwater deposition; tundra-derived peat; subaerial desiccation.				
East-central Norton Sound.	Holocene silty fine sand and sandy silt, bioturbated, 1-2 m thick, over	Yukon River. Medium energy deposition,	Biogenic	Medium	Medium	Low
	Pleistocene freshwater peaty mud.	Freshwater deposition; tundra-derived peat; subaerial desiccation.				
Eastern Norton Sound and Port Clarence Embayment.	Holocene sandy clayey silt, over	Yukon River and streams discharging from nearby shorelines. Low energy. deposition.	Biogenic	Low	Low	Low
	Pleistocene freshwater peaty mud and (or) glacial till.	Origin of Pleistocene peaty mud, same as above.				
Sand-wave fields near Port Clarence in Chirikov Basin	Late Pleistocene transgressive sands, over	Sand derived from pre-Quaternary bedrock and glacial moraines.	Biogenic	High	Very strong	Low
	Pleistocene freshwater peaty mud and (or) glacial till.	Origin of Pleistocene peaty mud, same as above.				



172°
170°
168°
166°
164°
162°
66°
65°
64°
63°
CHUKCHI SEA
U. S. S. R.
BERING STRAIT
ALASKA
78-21
Port Clarence
78-15
78-16
78-17
78-14
SEWARD PENINSULA
CHIRIKOV BASIN
NOME
NORTON SOUND
78-4
78-3
78-2
78-5
78-1
78-6
78-9
76-125
76-133
76-121
78-10
76-137
76-154
78-8
Stuart Island
78-24
76-156
78-22
78-23
St Lawrence Island
BERING SEA
YUKON DELTA
0 50 100 KILOMETERS



EXPLANATION

Solid symbol (•, ▲) shows data from core used Primarily for geologic analyses

Open symbol (o, △) shows data from core used primarily for gas and engineering analysis

Symbols for shear strength data:
- △, A pocket penetrometer
- o, . hand vane
- ▽,▼ lab vane
- ◻, ■ unconfined compression

Symbols for density data:
- 0, • Based on subsamples
- △,▲ Based on tube sections ~1 m long

Symbol for Alterberg Limits:

Plastic limit |———| Liquid limit

These data are few because the materials are generally nonplastic

Symbols for lithology:
- Sand
- Silt
- Clay
- Organic silt or clay
- Peat and highly organic soils

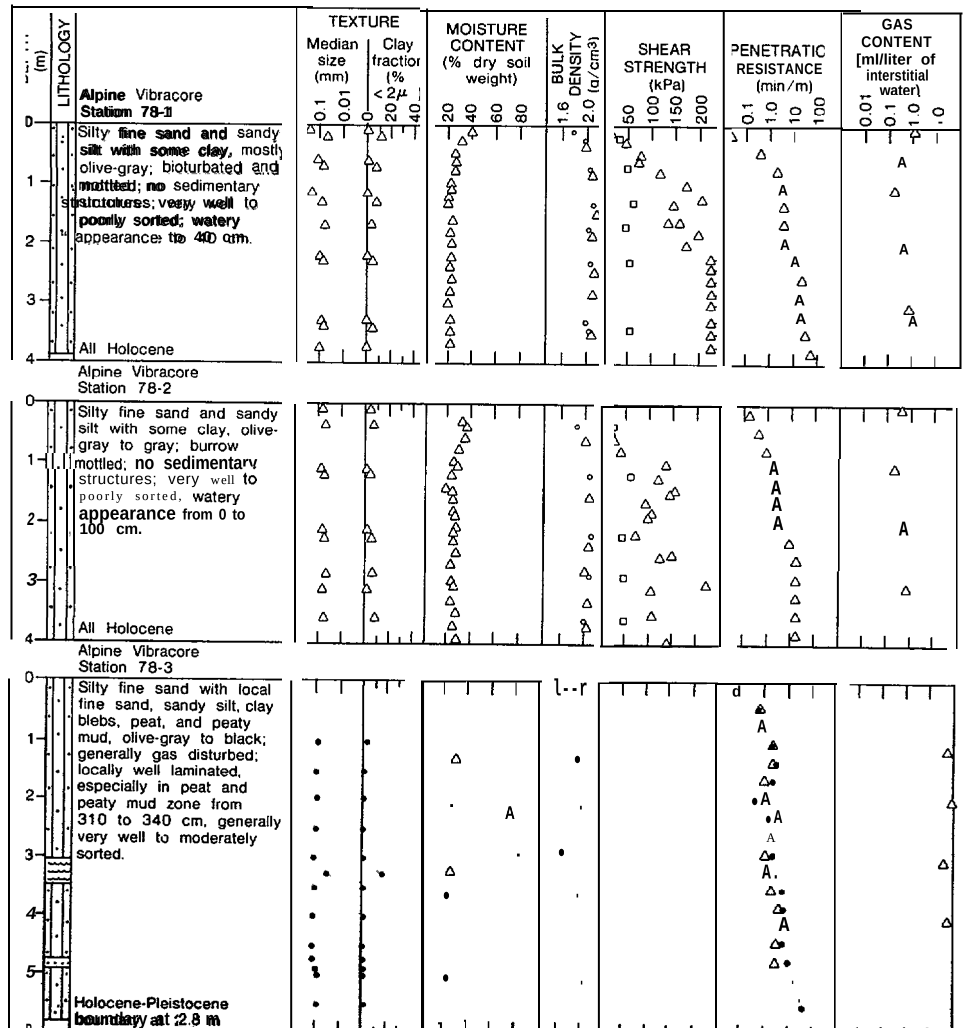
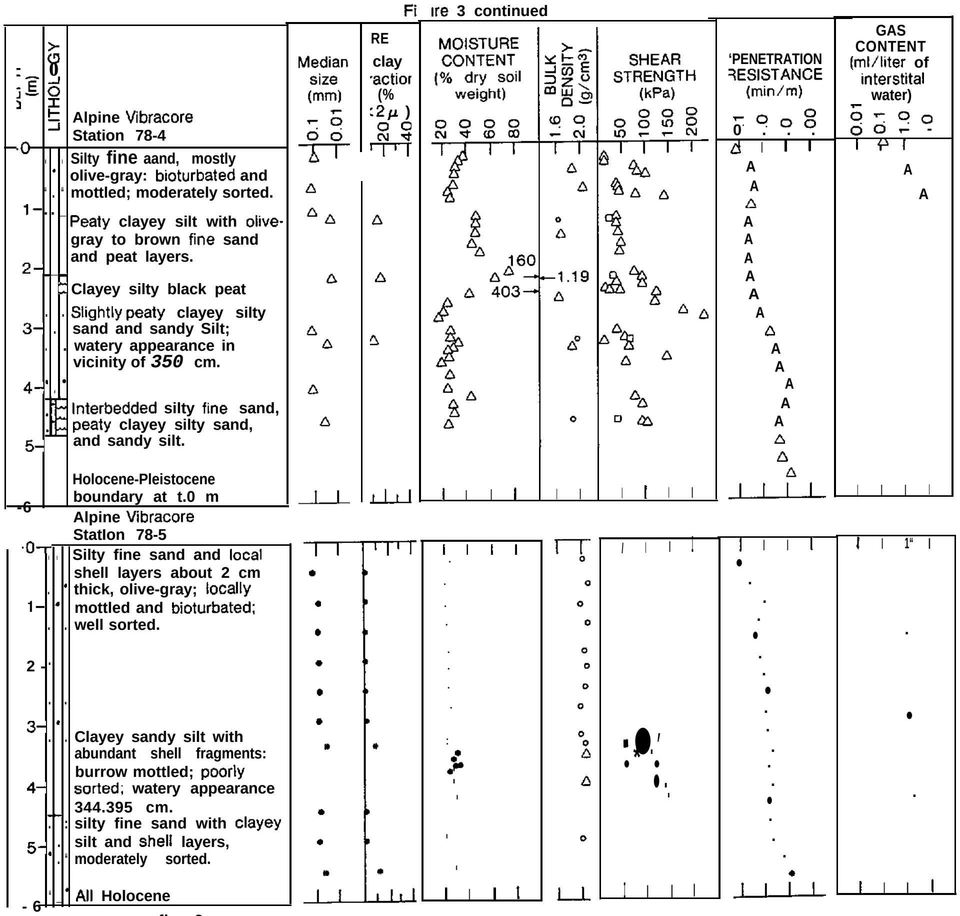
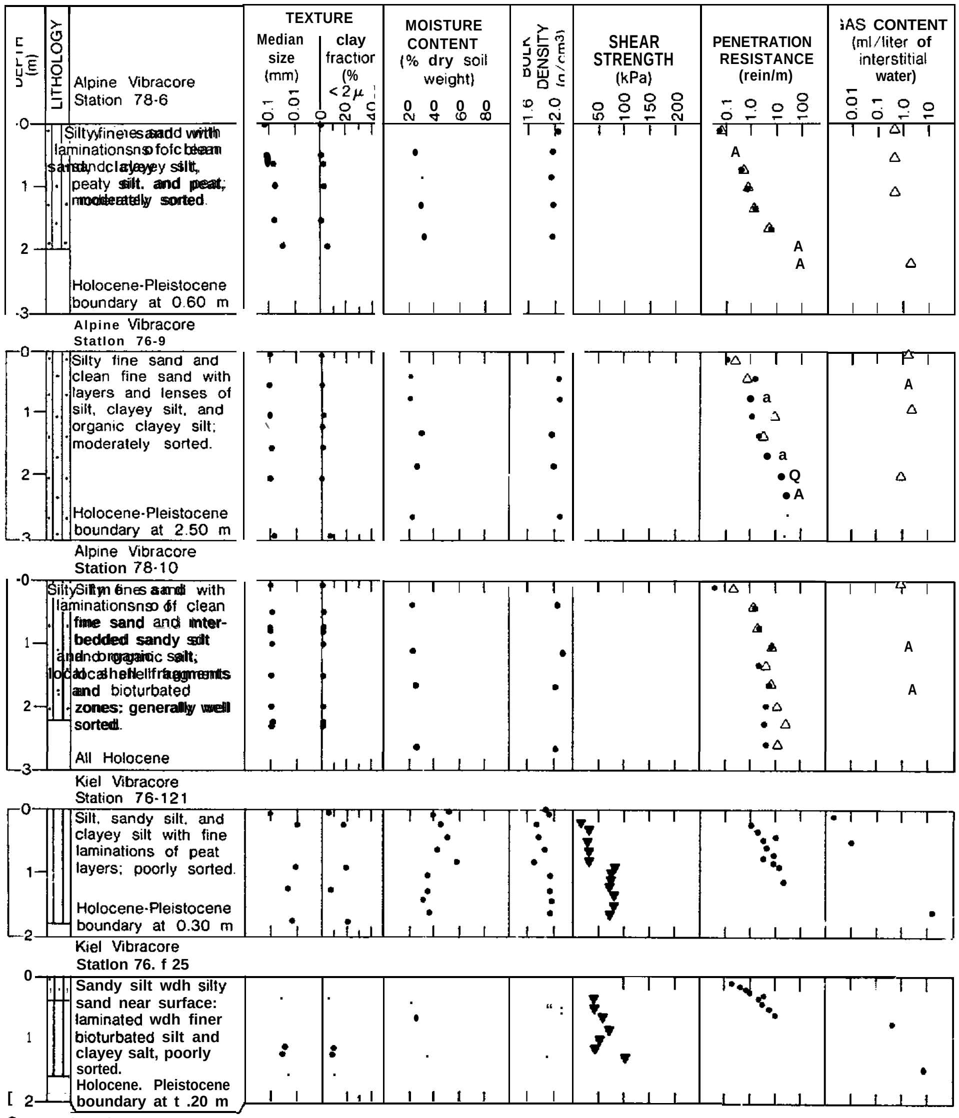


Figure 3 Continued on following page

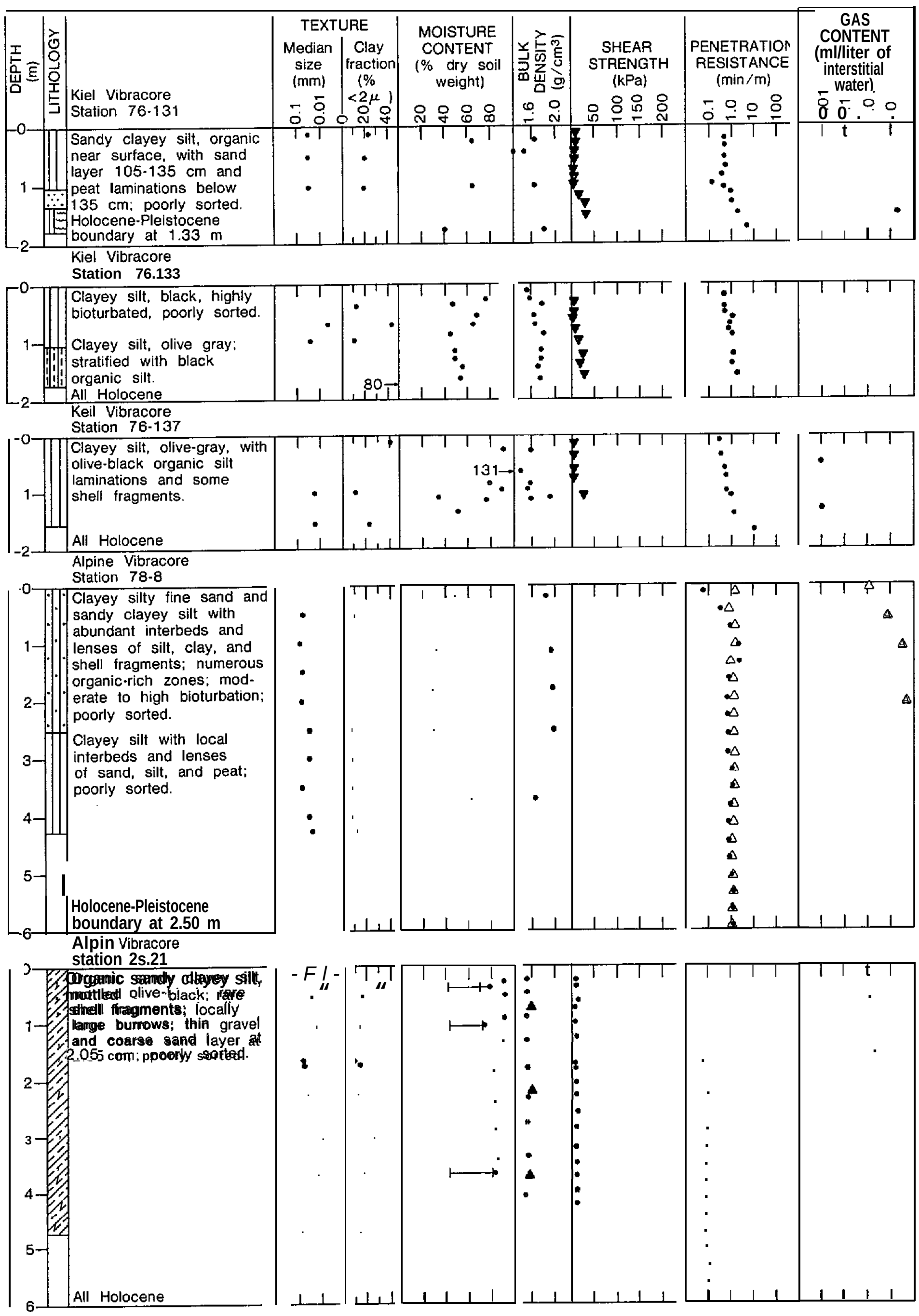
Fi ıre 3 continued



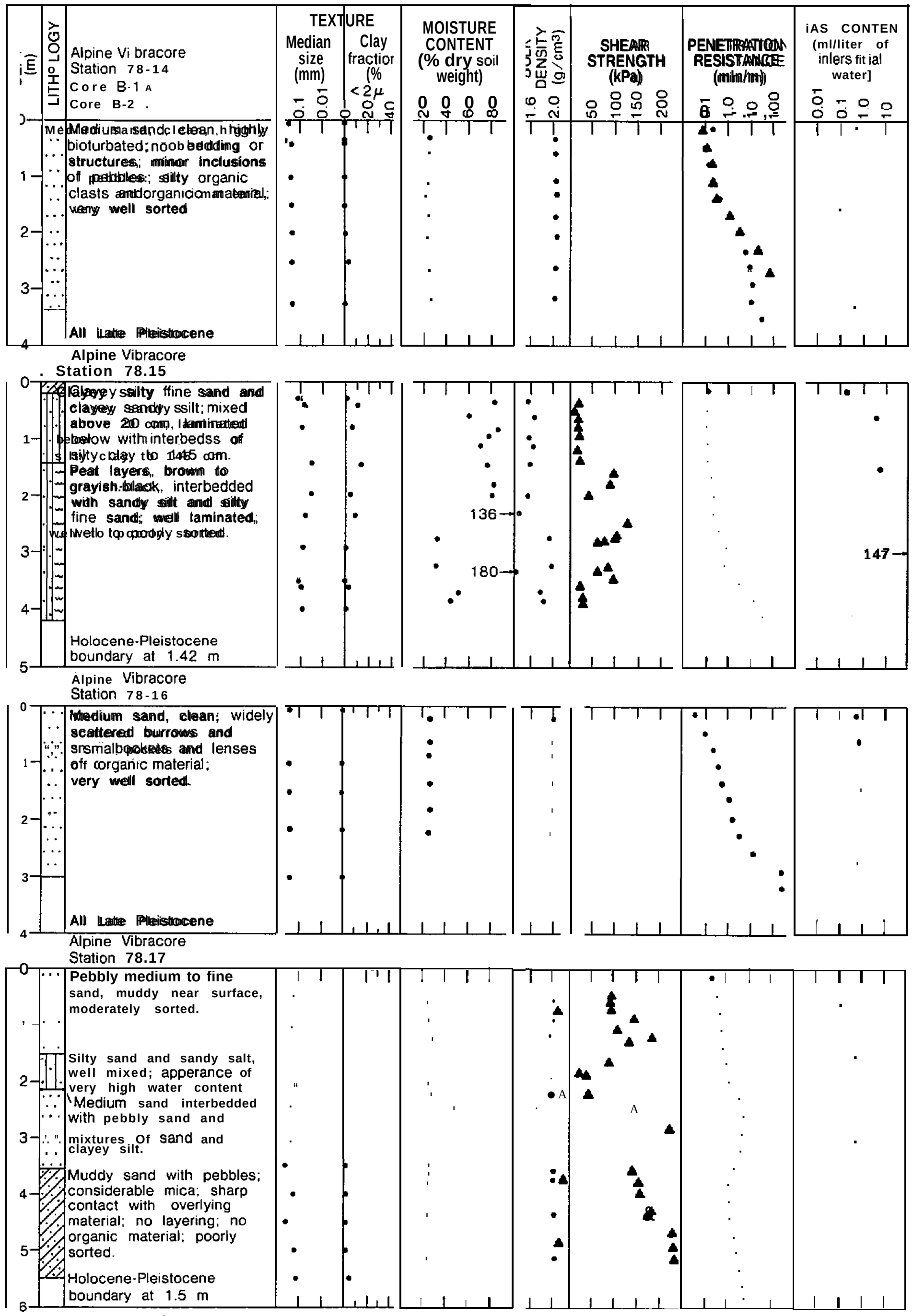
See explanation on fig. 2



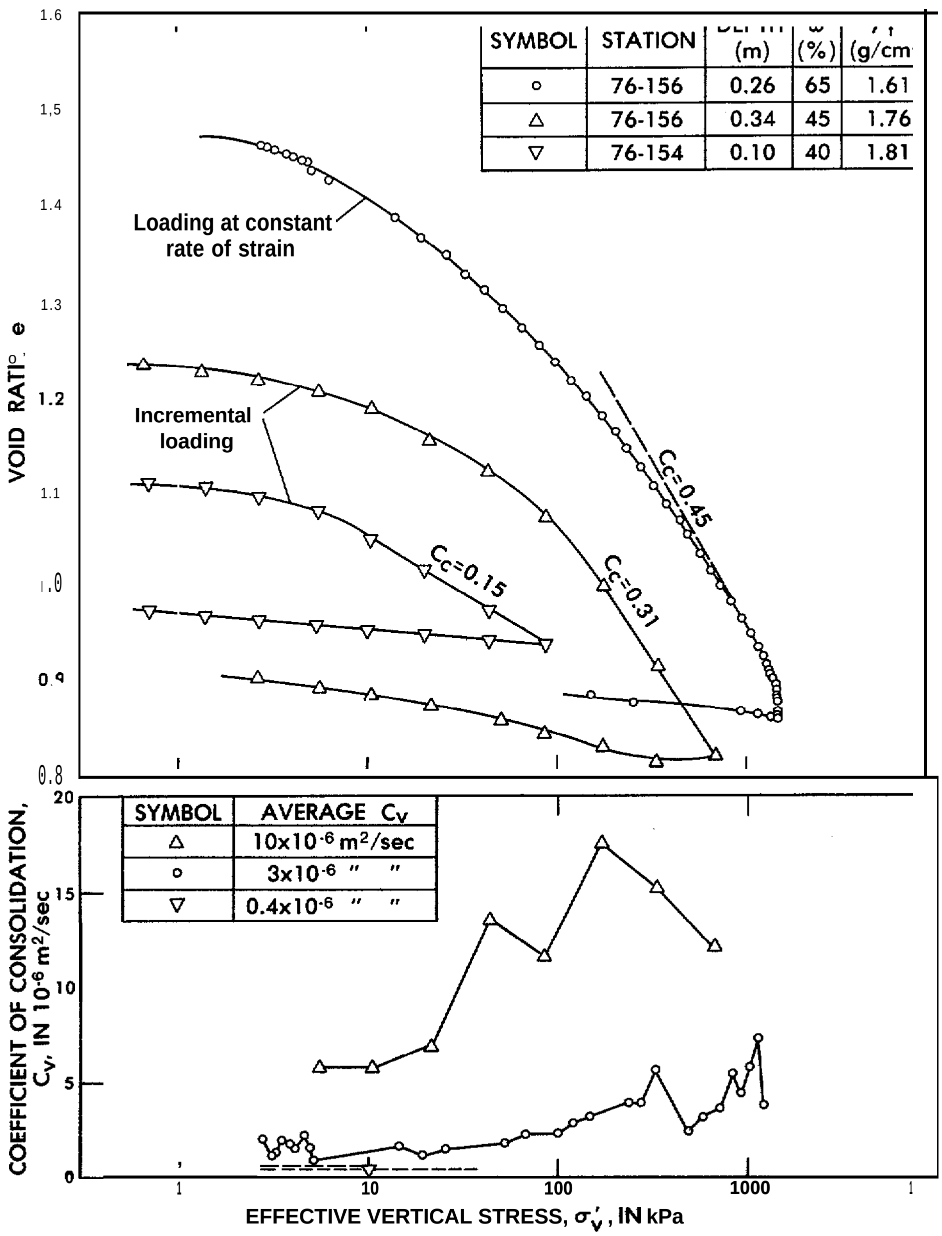
See explanation on fig. 2

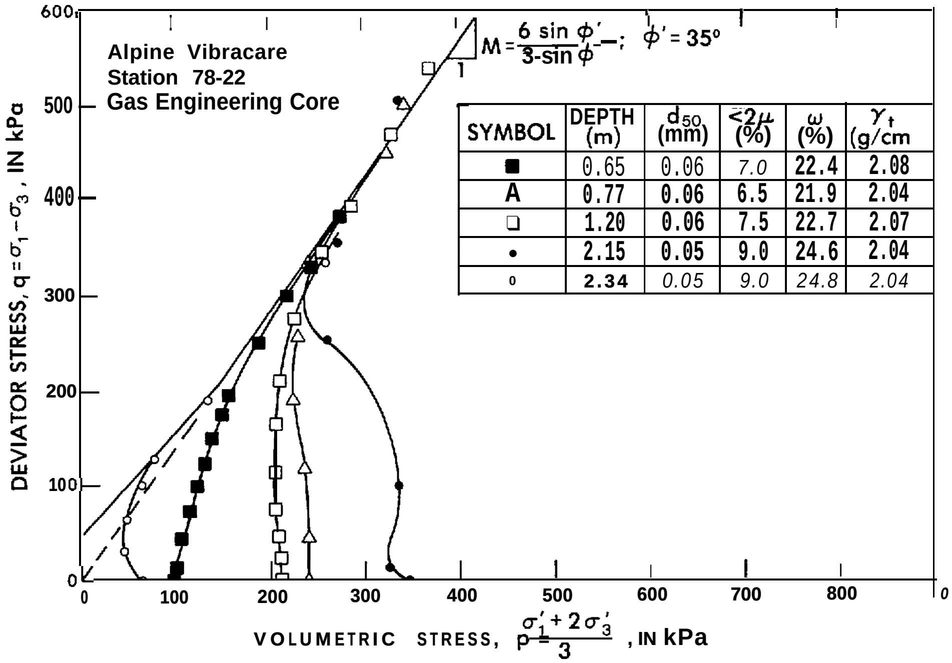


See explanation on fig. 2

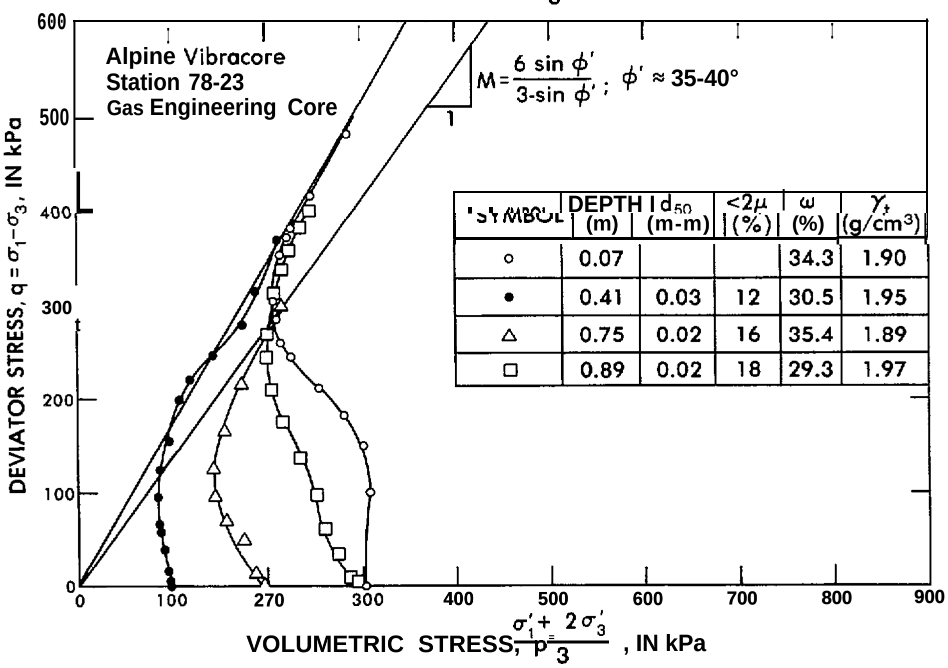


See explanation on fig. 2

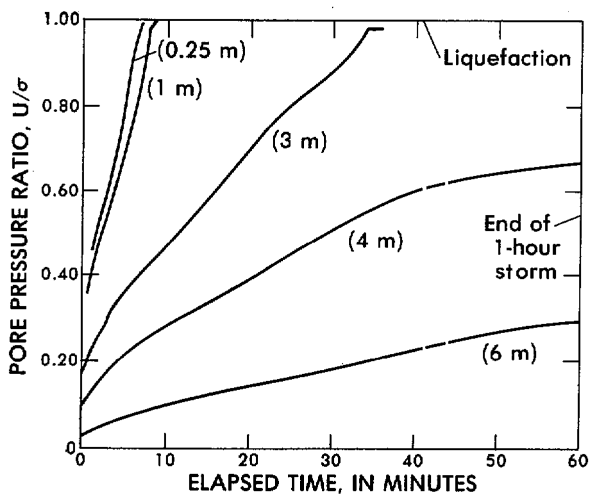

SYMBOL
STATION
(m)
(%)
(g/cm
76-156
0.26
65
1.61
76-156
0.34
45
1.76
76-154
0.10
40
1.81
Loading at constant rate of strain
Incremental loading
Cc=0.45
Cc=0.15
Cc=0.31
VOID RATIO, e
SYMBOL
AVERAGE Cv
10x10-6 m2/sec
3x10-6 " "
0.4x10-6 " "
COEFFICIENT OF CONSOLIDATION, Cv, IN 10-6 m2/sec
EFFECTIVE VERTICAL STRESS, σ'v, IN kPa



SYMBOL	DEPTH (m)	d_{50} (mm)	<2μ (%)	ω (%)	γ_t (g/cm
■	0.65	0.06	7.0	22.4	2.08
A	0.77	0.06	6.5	21.9	2.04
□	1.20	0.06	7.5	22.7	2.07
•	2.15	0.05	9.0	24.6	2.04
o	2.34	0.05	9.0	24.8	2.04



SYMBOL	DEPTH (m)	d_{50} (m-m)	<2μ (%)	ω (%)	γ_t (g/cm³)
○	0.07			34.3	1.90
•	0.41	0.03	12	30.5	1.95
△	0.75	0.02	16	35.4	1.89
□	0.89	0.02	18	29.3	1.97



PORE PRESSURE RATIO, U/σ
1.00
0.80
0.60
0.40
0.20
0
0
10
20
30
40
50
60
ELAPSED TIME, IN MINUTES
(0.25 m)
(1 m)
(3 m)
(4 m)
(6 m)
Liquefaction
End of 1-hour storm