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Geotechnical characterization of calcareous sediments from the Dry Tortugas Keys and Marquesas Keys CBBL SRP study sites, Lower Florida Keys

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Abstract Geotechnical characteristics of carbonate sediments from two test sites (Dry Tortugas Keys and Marquesas Keys) in the Lower Florida Keys were investigated as part of the Coastal Benthic Boundary Layer Special Research Program, through an extensive field coring and laboratory testing program conducted by the Marine Geomechanics Laboratory of the University of Rhode Island. Based on results from physical measurements, water content and wet bulk density values for both sites generally showed large variations in the upper 25 cm and little variation below this depth. Sediment samples exhibited low plasticity or nonplastic characteristics. Constant-rate-of-deformation consolidation test results showed strong apparent overconsolidation (stress state ratio >7.5) in the surface sediments (upper 50 cm) at the Dry Tortugas Keys, and light overconsolidation (stress state ratio <1.5) below 50-cm depth at the Marquesas Keys site. In-situ permeability values were between 10^{-4} and 10^{-7} cm/s at both sites and showed no strong depth dependence in the upper 2 m. Undrained shear strength profiles for Dry Tortugas Keys sediments indicated a marked stiffening with depth, whereas the Marquesas Keys sediments showed a gradual increase with depth. Consolidated isotropically undrained triaxial shear strength test results indicate that the undisturbed sediments had an average effective angle of internal friction of 38°, which is not fully realized until large axial strains on the order of 11% have accumulated. Evidence of cementation was not found in triaxial compression or consolidation test results. The general behavior and characteristics of these sediments are similar to those of granular materials, which is primarily due to their high calcium carbonate contents and lack of cementation.

Keywords Calcareous sediments · Carbonate sand · Coral sand · Soil mechanics · Geotechnical properties · CRD consolidation testing · CIU triaxial testing · Lower Florida Keys

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Introduction

The aim of the recently completed Coastal Benthic Boundary Layer Special Research Program (CBBL SRP), sponsored by the Naval Research Laboratory, Stennis Space Center, MS, was to characterize coastal benthic zone processes and sediments with particular attention to the acoustic behavior of seabed sediments. As a part of the overall program, a two-week research cruise was conducted at the CBBL SRP test sites in the Lower Florida Keys (Fig. 1), with the objective of characterizing the benthic boundary layer processes and sediments of the region (Lavoie et al. 1997). The sediments at the Lower Florida Keys sites vary from carbonate sands to clays with varying amounts of shells and shell fragments. The major geologic formation is the Key Largo Limestone, which underlies Pleistocene oolite and Holocene carbonate muds. Wind and waves play a major role in the distribution of carbonate debris from coral reefs, creating deposits of carbonate sands and muds in the troughs of the limestone. Plates from the calcareous *Halimeda* alga compose much of the sediment. At the Quicksands site (Fig. 1), *Halimeda* sands form 1- to 2-m-high sand waves (Davis et al. 1995).

In general, calcareous bioclastic sediments are composed of weak angular particles of varying sizes with relatively high void ratios and uneven cementation (Mitchell 1993). Grains typically consist of whole or fractured soft skeletal remains of calcareous plants and animals, which generally form a loosely packed sediment

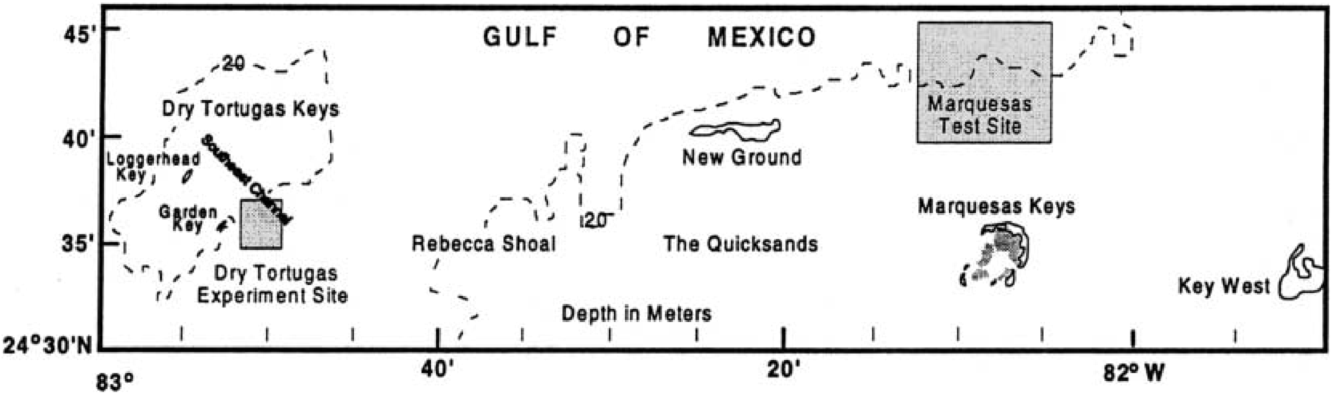

Fig. 1 Dry Tortugas Keys and Marquesas Keys CBBL SRP study site locations at the Lower Florida Keys

microstructure containing as much as 45% intraparticle pore space (Valent et al. 1982). The combination of these characteristics leads to high compressibilities, low strengths on initial loading, and large volume reductions during shear. Chemical processes associated with the dissolution and precipitation of calcium carbonate in the pore water lead to variable cementing of the sediment grains. Cemented sediments tend to show pseudo-preconsolidation stresses and exhibit a stiff brittle response to loading (Clough et al. 1981).

Sediments having in excess of 30% carbonate material are considered carbonate sands (Datta et al. 1981). Nacci et al. (1975) and Demars et al. (1976) found that for carbonate contents above 40%, sediments exhibited essentially granular behavior, whereas sediments with less than 40% carbonate tended to exhibit cohesive behavior. Considerable variations in the behavior of carbonate sands have been observed by a number of researchers, and are primarily due to the complex nature of the material itself. Datta et al. (1982) attribute the unusual behavior of carbonate sands to two primary factors: (1) the susceptibility of carbonate grains to crushing under loading; and (2) the cementation characteristics of the carbonate material.

Geotechnically, the strength and compressibility behavior of carbonate sediments is influenced by particle crushing, particle angularity, and cementation (Semple 1988). Datta et al. (1979) observed that particle crushing during shear is considerably more pronounced than during isotropic compression. They noted that effects of particle crushing manifest themselves in several ways: (1) reduction of the maximum principal effective stress ratio, (2) alteration of volume change behavior from dilative to contractive, (3) change from brittle to plastic behavior, and (4) increase in the failure strain. In addition, shear strength test results also indicate that carbonate sands typically have higher friction angles than silica sands, which may be due to particle angularity and crushing effects (Noorany 1982; Semple 1988), tending to increase with increasing carbonate content (Demars et al. 1976). Carbonate sands have also been found to be considerably more compressible than silica sands and tend to crush easily due to their relative softness and high porosity (Poulos et al. 1984).

This paper summarizes results from the geotechnical characterization of sediments from the Dry Tortugas Keys and Marquesas Keys study sites based on field and laboratory investigations conducted by the Marine Geomechanics Laboratory (MGL) of the University of Rhode Island. Although not the primary focus of this paper, some geoacoustic data collected by the MGL indicating relationships with geotechnical properties are also included.

Field sampling

Sixty-nine large-diameter gravity cores (GC) and 11 box cores (BC) were obtained by University of Rhode Island Marine Geomechanics Laboratory (URI MGL) personnel in collaboration with Texas A&M University (TAMU) from the two prime study sites at the Marquesas Keys and the Dry Tortugas Keys (Fig. 1) to evaluate sediment geotechnical and acoustic properties. Gravity cores had an inside diameter of 10.6 cm, and box-core dimensions were 50×50×50 cm. Gravity cores provide representative sediment samples with maximum penetration depth and minimal disturbance. Box cores are used to obtain multiple high-quality samples with minimum disturbance at a single depth in surficial sediments. Maximum penetration depth was 300 cm for gravity cores and 35 cm for box cores. From among those obtained, 35 gravity cores and 11 box cores were available to the URI MGL for processing, laboratory testing, and analysis. Details of the coring equipment and procedures are described in the MGL Key West Campaign cruise report (Silva and Brandes 1995).

Materials and methods

Core processing

Most of the gravity cores contained between 1 and 3 m of intact sediment. Eight of the cores were processed vertically using a pneumatic piston apparatus for extrusion. The remaining cores were split lengthwise for subsampling and visual description. Undisturbed sediment samples were taken in thin-walled stainless steel tubes at regular intervals for consolidation testing (compressibility, permeability, stress history), and triaxial compression strength testing (stress-strain-strength behavior). Bulk samples were also obtained for physical and index properties determinations (water content, specific gravity, grain-size distribution, calcium carbonate content, Atterberg limits). In addition, all gravity cores were photographed along their entire lengths.

Evaluation of wet bulk density and compressional wave velocity using the MSCL

Sediment wet bulk density, compressional wave velocity, and attenuation coefficient were measured using a Geotek multisensor core logger (MSCL) prior to opening gravity cores for further processing. The MSCL is a computer-controlled, automated data acquisition system, consisting of a conveyor which moves intact whole core sections past a series of stationary sensors perpendicular to the core tube. Wet bulk density is measured using a ^{137}Cs radioactive source and a scintillation counter measurement system (Schulteiss and Weaver 1992). Compressional wave velocity (P-wave velocity) and attenuation are measured using a set of spring-mounted piezo-ceramic transducers operating at 500 kHz. A set of displacement transducers is used to measure the deviations in core diameter. Corrections are made for the presence of the core liner. Measurements of wet bulk density and compressional wave velocity were made at 1-cm intervals along the length of each intact whole core section.

Water content, wet bulk density, and Atterberg limits

Water contents were determined on a mass basis according to ASTM D216 (ASTM 1994). In the gravity cores, sampling intervals were approximately every 1 to 5 cm in the upper 40 cm, and approximately every 10 to 15 cm below 40 cm. Water content samples were also obtained from box cores at selected intervals. Values of water content are reported on a dry weight basis (relative water content) and were corrected for 35 ppt salt content.

During core processing, values of wet bulk density were determined using a thin-walled, constant-volume plug sampler to obtain samples at about 25-cm intervals along the lengths of the split core sections where possible. In several gravity cores, wet bulk density determinations were difficult or impossible due to the presence of shell clusters or coarse, loose sand. Wet bulk density values were also calculated from measured water content values by assuming that the sediment was saturated and by using an average specific gravity of solids of 2.80.

Atterberg limit values (plastic limit and liquid limit) were determined according to ASTM D4318 (ASTM 1994) on material which passed the No. 40 (0.425-mm) U.S. Standard Sieve. The natural salinity of the sediments was maintained during testing. The Atterberg limits are an indication of changes in the consistency of fine-grained sediments with changes in water content.

Specific gravity of solids, carbonate content, and grain size

Values of the specific gravity of solids were determined using the pycnometer method, which is based on the volumetric displacement and mass of material according to ASTM D854 (ASTM 1994). The specific gravity of solids is the nondimensional notation of grain density. All values of the specific gravity of solids were corrected for 35 ppt salt content. Calcium carbonate contents (dry mass %) were determined in one gravity core from each of the two study areas (Marquesas Keys and Dry Tortugas Keys) by assuming all inorganic carbon was present as calcium carbonate. A Coulometrics Inc. Model 5011 CO_2 coulometer with a Model 5030 carbonate content apparatus was used for this purpose. Grain-size distributions were determined by a combination of wet sieve analysis and the pipette method. The sand (0.062 to 2 mm) and gravel (> 2 mm) fractions were separated by mechanical sieving according to ASTM D422 (ASTM 1994). The fractions passing the No. 230 U.S. Standard Sieve (< 0.062 mm) were analyzed by the pipette method (Folk 1974), which is based on the settling velocity of individual particles according to Stoke's law.

CRD consolidation and permeability

A series of constant-rate-of-deformation (CRD) back-pressured consolidation and permeability tests was performed on 5.08-cm-diameter, 1.90-cm-thick, undisturbed sediment samples. The MGL CRD system has automated data acquisition capabilities and uses flow pump technology, which allows specimens to be consolidated at a constant rate of strain. The flow pumps are also used to make direct measurements of permeability at various void ratios during the consolidation process without disturbing the sediment. Samples were consolidated to effective stresses (σ'_o) of about 100 kPa for Dry Tortugas Keys sediments and to about 1,000 kPa for Marquesas Keys sediments. Strain rates were selected to limit excess pore pressures to less than about 10% of the target effective stress. Details of the apparatus and testing procedures are described elsewhere (Ag 1994; Brandes et al. 1996). The tests were conducted in general accordance with ASTM D4186 (ASTM 1994).

Undrained shear strength

Undrained shear strengths were measured in all gravity cores using a motorized miniature vane (12.7×12.7 mm) shear apparatus equipped with an electronic torque transducer. The rotation rate of the vane was 60°/min in all tests. Shear strength measurements were typically made at about 25-cm intervals along the length of split core sections, although the test could not be done at several locations due to the presence of shell clusters. Undrained shear strength measurements using vane shear devices are only valid for fine-grained sediments (silt size and finer) and therefore, measurements were not made in coarser grained materials. A Brookfield viscometer, fitted with an 8×8-mm miniature vane and rotated at 0.5 rpm, was used to make undrained shear strength measurements in the box cores where fine-grained sediment was evident.

As a part of the MGL research program, consolidated isotropically undrained (CIU) triaxial compression shear strength tests were conducted according to ASTM D4767 (ASTM 1994) by Pizzimenti (1996), and Sykora (1998). Procedures specific to the MGL triaxial flow pump system are in accordance with those developed by Wikar (1993) and Brogan (1995). Triaxial samples were 5.08 cm in diameter and 10 cm long and were back-pressured to ensure complete saturation. Isotropic consolidation was performed using a CRD flow pump system at a volumetric strain rate of approximately 0.0025% per minute to effective stresses ranging from 1.2 to 34 kPa. Undrained shear strength testing was conducted at an axial strain rate of 2% per hour until failure using a constant rate of strain load frame. Details of the apparatus and testing procedures are described elsewhere (Pizzimenti 1996; Pizzimenti and Silva 1997; Sykora 1998).

Table 1 Specific gravity and Atterberg limit values for sediments from the Dry Tortugas Keys study site. All specific gravity and Atterberg limit values are corrected for 35 ppt salt content. *n.d.* Not determined; *NP* nonplastic

Core	Depth (cm)	G_s	PL (%)	LL (%)
KW-SJ-GC-214	3	2.81	35	42
	23	n.d.	34	38
	43	n.d.	NP	n.d.
	83	n.d.	NP	n.d.
	123	n.d.	NP	n.d.
	148	n.d.	21	32
KW-SJ-BC-216	1	2.85	37	45
	11	2.83	36	40
	16	2.75	34	40
	21	2.78	33	39
KW-SJ-GC-232	13	2.85	NP	n.d.
KW-SJ-GC-257	127	2.86	n.d.	n.d.
KW-SJ-GC-269	23	2.77	n.d.	n.d.
KW-SJ-GC-285	3	2.86	NP	n.d.
	58	n.d.	NP	30
	78	2.83	n.d.	n.d.
KW-SJ-GC-301	3	n.d.	NP	n.d.
	33	2.80	NP	n.d.
	63	n.d.	NP	n.d.
KW-SJ-GC-313	2	2.79	NP	n.d.
	13	2.73	NP	n.d.
	24	2.79	NP	n.d.
	32	2.79	NP	n.d.
	47	2.77	NP	n.d.
	84	2.82	NP	n.d.
	111	2.80	NP	n.d.
	139	2.80	24	33
	188	2.79	24	39
KW-SJ-GC-321	27	2.84	33	n.d.
	44	2.84	n.d.	n.d.
	145	2.84	n.d.	n.d.

Statistics

A statistical analysis of some of the data was done and interrelationships between various geotechnical parameters were assessed by means of linear regression analyses. The coefficient of determination (r^2), an indication of how much of the data is explained by the equation of the fit, is reported with each relationship.

Results

Dry Tortugas Keys site

Physical and index properties

Core sampling at the Dry Tortugas Keys site was generally difficult due to the presence of coarse sands and shell material, limiting most core recovery lengths to less than 200 cm (Table 1). Core locations are shown in Fig. 2. Most of the cores from the Dry Tortugas Keys site indicate a decrease in water content from about 55% just below the surface to about 45% at 25-cm depth (Fig. 3). Below 25 cm there was a gradual reduction in water content to about 40% at 50-cm depth. The overall reduction in water content continued to 200 cm (Fig. 4). Values of wet bulk density showed a rapid increase immediately below the surface and a gradual increase with depth below 25 cm to a maximum value of about 1.90 g/cm^3 (Figs. 3 and 4). Despite the larger sampling interval during core processing as compared with the MSCL, the water content and density profiles showed the same trends. In general, there was good agreement between the wet bulk density values obtained from the core logger and those determined from water content measurements. The variations of water content (w) and wet bulk density (ρ_t) with depth (z) for the upper 50 cm at this site can be approximated as:

$$w(\%) = 58.2(z)^{-0.087} \tag{1}$$

for which $r^2 = 0.295$, and

$$\rho_t(\mathrm{g/cm^3}) = 1.76(z)^{0.012} \tag{2}$$

for which $r^2 = 0.207$.

When all data were included to a depth of 200 cm:

$$w(\%) = 58.0(z)^{-0.086} \tag{3}$$

for which $r^2 = 0.451$, and

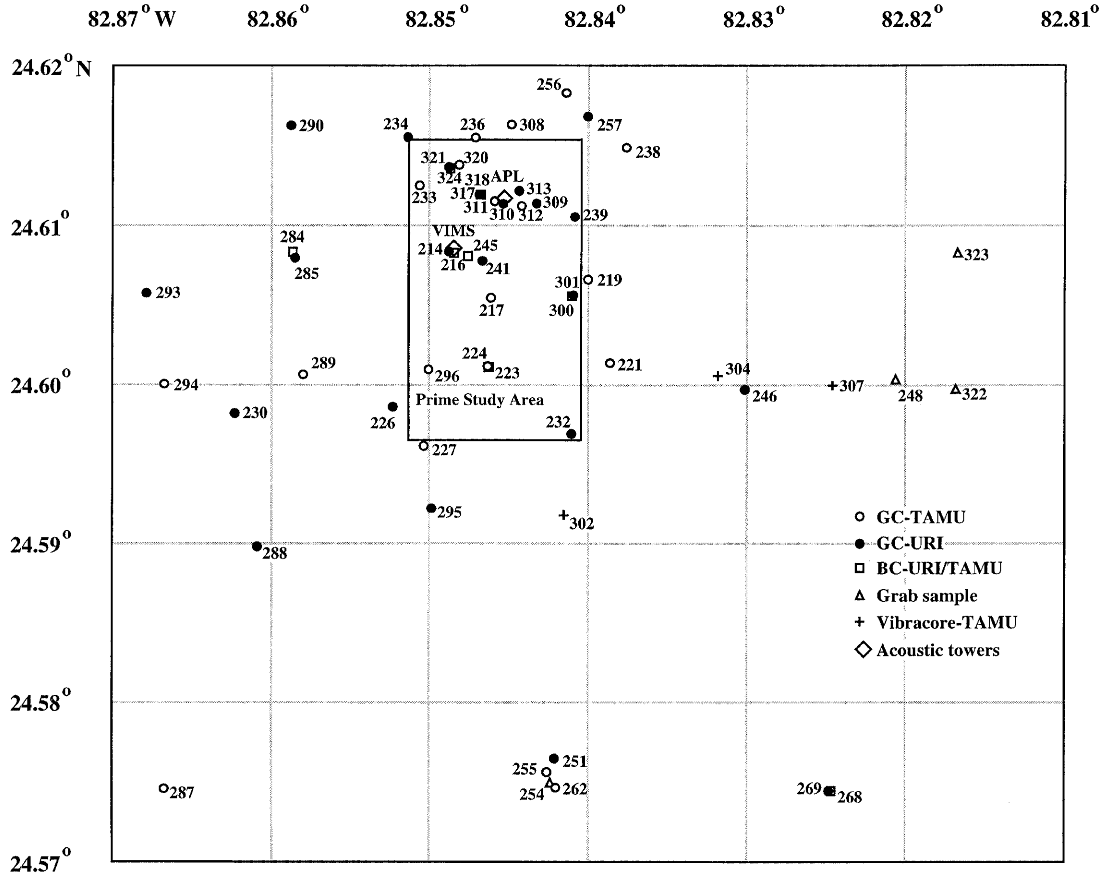

Fig. 2 Core locations at the Dry Tortugas Keys study site

$$\rho_t(\text{g/cm}^3) = 1.75(z)^{0.016} \quad (4)$$

for which $r^2 = 0.407$. Equations (1) and (2) show moderate correlations of w and ρ_t with depth for the upper 50 cm of sediment (Fig. 3); coefficients of determination were somewhat low. When all the data were included (Fig. 4), the correlations with depth were better (Eqs. 3 and 4).

Calcium carbonate content values for the Dry Tortugas Keys sediments showed little variation with depth (average value 93% by weight; Fig. 5). The calcium carbonate contents were slightly higher than those documented at the Marquesas Keys site (see below). Values of specific gravity of solids (G_s) ranged from 2.71 to 2.90 (Table 1; Fig. 5).

Most samples from the Dry Tortugas Keys site were determined to be nonplastic from Atterberg limit tests (Table 1). However, the other samples showed average values of 31 and 38% for plastic limits (PL) and liquid limits (LL), respectively, with an average plasticity index (PI) of 8% (Table 2). These sediments are low plasticity clayey silts and are classified as ML based on the Unified Soil Classification System (ASTM 1994). The in-situ water contents of these low plasticity sediments were generally above the LL values (Fig. 6).

At the Dry Tortugas Keys site, sediments consist of sand, carbonate mud, and shell fragments (Table 3). The sediments consist primarily of fine to coarse well-graded sands which are angular to subangular, and silt with occasional small amounts of gravel. Grain size was relatively constant, and average values of 6% gravel, 56% sand, 28% silt, and 10% clay were recorded in the upper 200 cm (Table 3). The sand fractions ranged from 21 to 73% in the upper 200 cm, and the fines were typically less than about 20%. Mean grain sizes varied from 0.008 mm ($\phi = 6.99$) to 0.536 mm ($\phi = 0.88$; Table 2).

In the eastern and southern sectors of the Dry Tortugas Keys site, sediments were generally coarser and denser than in the northern and western sectors of the site (Table 3). There was more spatial variation in physical and index properties across the Dry Tortugas Keys site than at the Marquesas Keys site (Tables 1, 3). However, index properties did not show large downcore variations.

Compressibility and permeability

Typical consolidation and permeability results from one-dimensional CRD tests of samples from core KW-SJ-GC-313 are shown in Fig. 7. Table 4 summarizes the results for the Dry Tortugas Keys site. The data show very low compression indices (C_c range: 0.145 to 0.250) and recompression indices (C_r range: 0.008 to 0.030). The compression and recompression indices indicate the change in deformation with applied stress for the

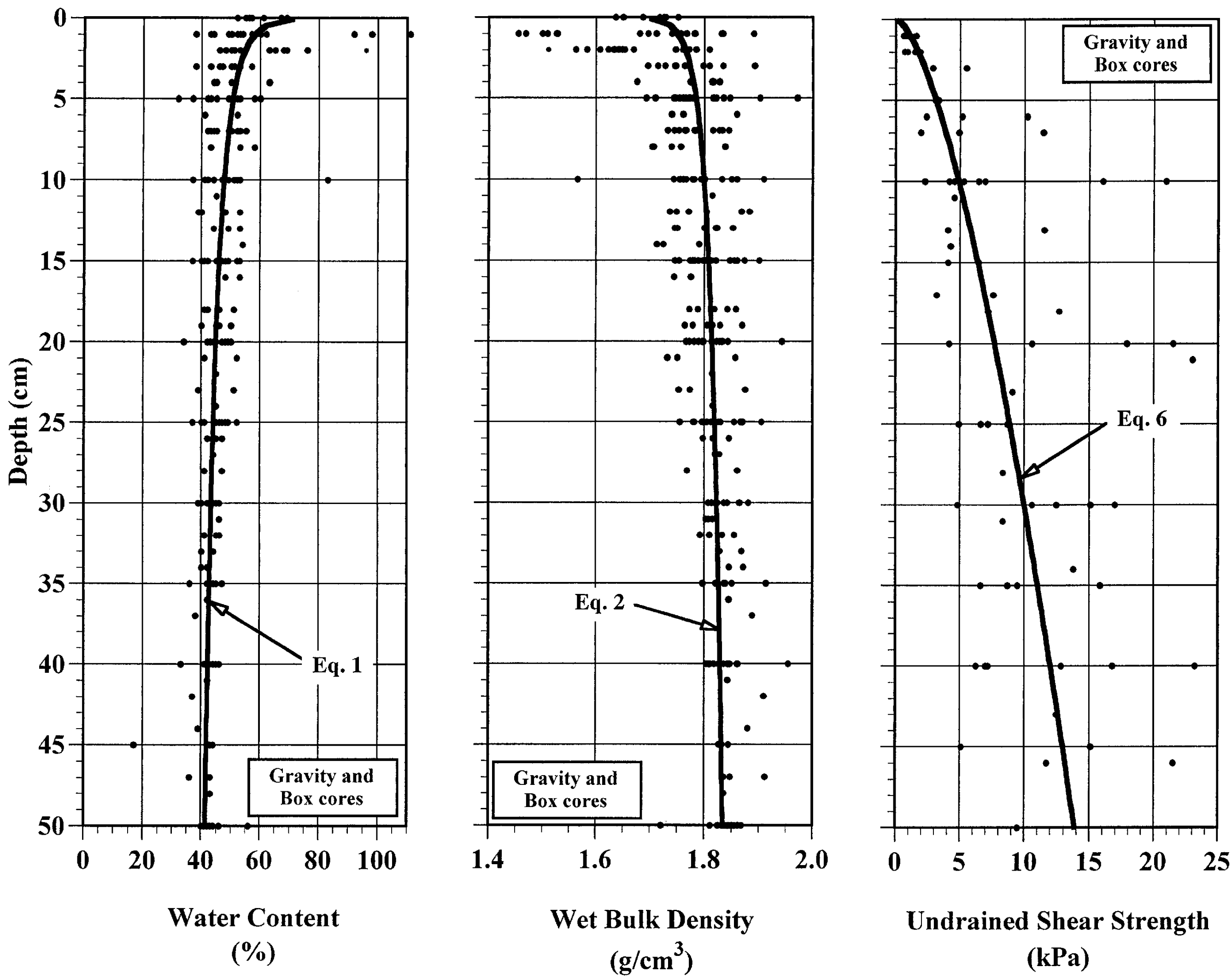

Fig. 3 Water content, wet bulk density and shear strength profiles for sediments from the Dry Tortugas Keys study site (upper 50 cm)

loading and unloading portions of the consolidation curves, respectively. These indices do not show a strong depth dependency for the Dry Tortugas Keys sediments.

The stress state ratio (*SSR*), or overconsolidation ratio (*OCR*), is an indication of stress state and is defined as (Lambe and Whitman 1969):

$$SSR = OCR = \frac{\sigma'_p}{\sigma'_o} \qquad (5)$$

where σ'_p is the past maximum vertical effective stress (preconsolidation stress), and σ'_o is the present in-situ vertical effective stress. *SSR* values ranged from 5.2 to 60 in the upper 300 cm, indicating strong apparent overconsolidation.

Consolidation data for the Dry Tortugas Keys sediments do not generally indicate a clearly defined preconsolidation stress. It was difficult to determine σ'_p from the consolidation data for these carbonate sediments, since the transition to the virgin compression curve was not well defined and there may have been some breakdown of carbonate grains during consolidation (Pizzimenti and Silva 1997). A gradual change in slope was observed in the consolidation data. *SSR* values trended toward a normally consolidated state with depth.

Values of permeability (k) at in-situ void ratios (e_o) were interpolated from permeabilities measured during CRD testing and ranged from 1.3×10^{-4} to 4.4×10^{-7} cm/s (Table 4). After initial testing, sample KW-SJ-GC-313 (149-cm depth) was mechanically remolded to the original initial void ratio and tested again (labeled 149-R depth in Table 4). Remolding significantly altered the sediment structure, resulting in a decrease in C_c from 0.205 to 0.140 and a decrease in k from 5.1×10^{-6} to 4.4×10^{-7} cm/s.

Undrained shear strength

Undrained shear strength measurements using the miniature vane apparatus for the Dry Tortugas Keys sediments generally showed strength values increasing with depth, typically from about 2.5 kPa near the surface to

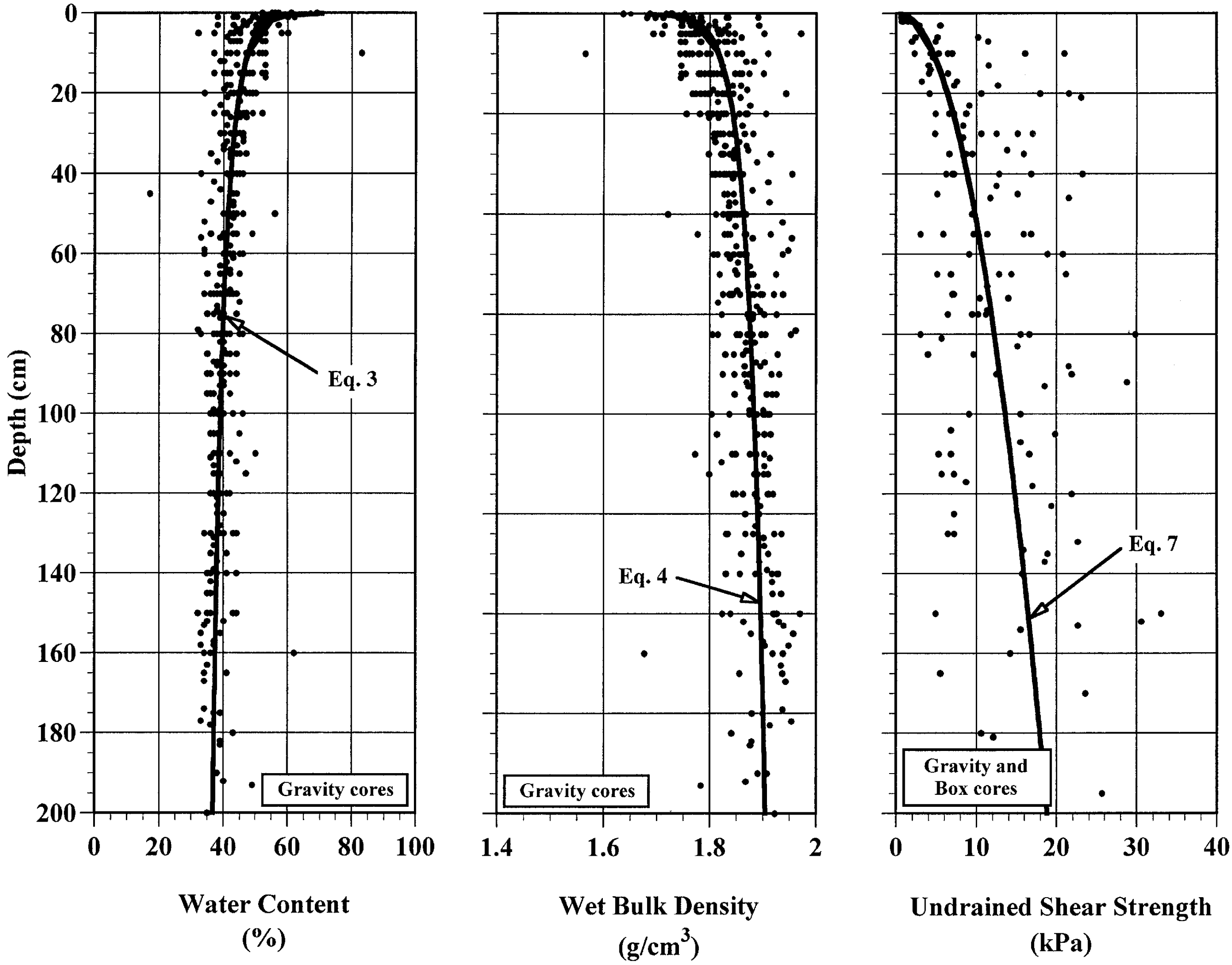

Fig. 4 Water content, wet bulk density, and shear strength profiles for sediments from the Dry Tortugas Keys study site (upper 200 cm)

about 25 kPa at depths greater than about 100 cm (Figs. 3 and 4). The variation of undrained shear strength (s_u) with depth for the upper 50 cm at the Dry Tortugas Keys site can be approximated as:

$$s_u(\text{kPa}) = 1.10(z)^{0.648} \quad (6)$$

for which $r^2 = 0.645$, and when all data were included to a depth of 200 cm:

$$s_u(\text{kPa}) = 1.56(z)^{0.470} \quad (7)$$

for which $r^2 = 0.532$. Equations (6) and (7) indicate reasonably good correlations of s_u with depth, particularly in the upper 50 cm. There does not appear to be any direct relationship between w and s_u for these sediments.

The results of the CIU triaxial compression shear strength tests are summarized in Table 5. Shearing behavior was characterized by an initially stiff deviatoric response and a defined knee at a small axial strain level, after which an ultimate state was reached. The ultimate condition occurred only at very large axial strains (25 to 30%). High positive pore pressures developed at about 5% axial strain, reducing thereafter due to specimen dilation but remaining positive throughout shearing in most tests. Axial compressive strain at failure ranged from 7 to 20.5%. Test results of undisturbed sediments indicate an average effective angle of internal friction of 38°, which was not fully realized until large axial strains on the order of 11% had accumulated.

The maximum effective stress ratio (σ_1'/σ_3') was used as the failure criterion since deviatoric stresses ($\Delta\sigma_d$) continued to increase during loading, and peak values were not achieved during shear. At failure, samples had an average effective angle of internal friction of 38°, which was not fully realized until large axial strains of about 11% had accumulated. Cohesion was found to be zero for all CIU shear strength samples.

The initial tangent modulus (E_i) shown in Table 5 is a measure of sediment stiffness. Values of E_i were determined from transformed axial stress-strain plots using Kondner's (1963) hyperbolic method, and they were correlated with the initial isotropic effective stress, for a

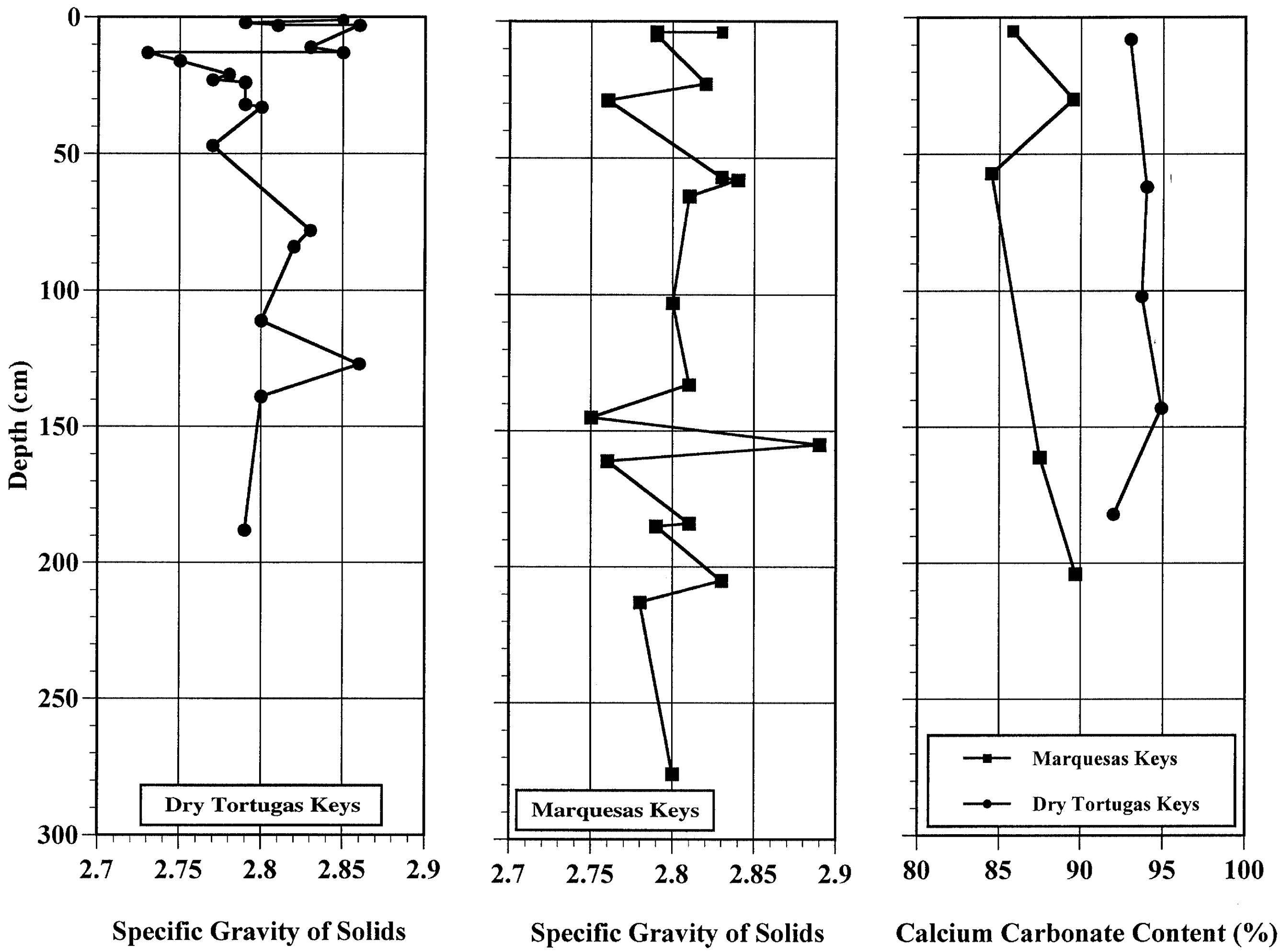

Fig. 5 Specific gravity of solids and calcium carbonate profiles for sediments from the Dry Tortugas Keys and Marquesas Keys study sites

range of stresses between 1.2 and 34.0 kPa. Using the data obtained from the Dry Tortugas Keys CIU tests, Pizzimenti and Silva (1997) obtained fitting parameters for the model proposed by Janbu (1963), which relates sediment stiffness and effective stress:

$$\frac{E_i}{p_a} = K\left(\frac{p'_o}{p_a}\right)^n \qquad (8)$$

where p'_o is the initial isotropic effective stress, p_a is atmospheric pressure, and K and n are empirical coefficients which depend on the rate of increase of modulus with stress. The empirical constants, K and n, were found to be 518 and 1.19, respectively, for undisturbed sediment ($r^2=0.790$), and 773 and 1.30, respectively, for remolded sediment ($r^2=0.980$). The value of n is zero for a purely elastic material, indicating no dependency of modulus on stress, and it approaches unity for loose sands (Lambe and Whitman 1969). Pizzimenti (1996), and Pizzimenti and Silva (1997) give a detailed analysis and discussion of the CIU strength test results.

Marquesas Keys site

Physical and index properties

Core sampling was generally easier at the Marquesas Keys site, with recovery lengths of up to 300 cm. Most recovered core lengths were in excess of 200 cm (Table 6). Core locations are shown in Fig. 8. Values of water content were near 45% in most of the cores from the Marquesas Keys site (Figs. 9 and 10), although variability exists with depth in individual cores. Wet bulk density values were generally lower (1.80 g/cm^3) in the top 25 cm compared with the Dry Tortugas Keys site. However, values of ρ_t for the Marquesas Keys sediments were lower at depths below 25 cm. Most of the Marquesas Keys cores showed considerable fine-scale (1 cm) as well as large-scale (on the order of 100 cm) variations. Generally, there was good agreement between values of ρ_t obtained from the core logger and those determined from water content measurements. The variation of w and ρ_t with z for the upper 50 cm at this site can be approximated as:

$$w(\%) = 64.2(z)^{-0.114} \qquad (9)$$

for which $r^2=0.432$, and

Table 2 Summary of physical properties, index properties and strength values for sediments from the Dry Tortugas Keys and the Marquesas Keys study sites. All specific gravity and Atterberg limit values are corrected for 35 ppt salt content. μ_{mm} Mean grain size (mm); μ_{ϕ} mean grain size (ϕ)

Site	W (%)	ρ_t (g/cm^3)	s_u (kPa)	G_s	PL (%)	LL (%)	PI (%)	μ_{mm} (mm)	μ_{ϕ} (ϕ)
Dry Tortugas Keys	Depth: 0 = z = 50 cm								
Average	47.6	1.81	8.0	2.80	35	41	6	0.105	3.25
Range	17–111	1.56–1.97	0.58–23.2	2.73–2.86	33–37	38–45	4–8	0.031–0.220	5.02–2.17
Standard deviation	9.8	0.054	5.9	0.039	1.5	2.5	1.6	0.063	3.99
Dry Tortugas Keys	Depth: 0 = z = 200 cm								
Average	43.9	1.85	10.8	2.80	31	38	8	0.127	2.97
Range	17–111	1.56–1.97	0.58–33.0	2.73–2.86	21–37	30–45	4–15	0.008–0.536	6.99–0.88
Standard deviation	8.8	0.059	7.1	0.036	6.1	4.7	3.5	0.120	3.05
Marquesas Keys	Depth: 0 = z = 50 cm								
Average	48.0	1.80	7.7	2.80	33	44	12	0.121	3.04
Range	35–91	1.53–1.93	1.7–19.6	2.76–2.83	28–36	39–52	8–16	0.010–0.313	6.66–1.66
Standard deviation	9.1	0.069	5.1	0.028	2.9	4.1	2.3	0.167	2.57
Marquesas Keys	Depth: 0 = z = 300 cm								
Average	47.5	1.80	9.9	2.80	28	43	15	0.089	3.49
Range	33–91	1.53–1.96	1.5–30.2	2.75–2.89	21–36	35–53	8–25	0.006–0.335	7.40–1.56
Standard deviation	8.0	0.065	5.3	0.033	4.1	4.1	4.7	0.125	2.99

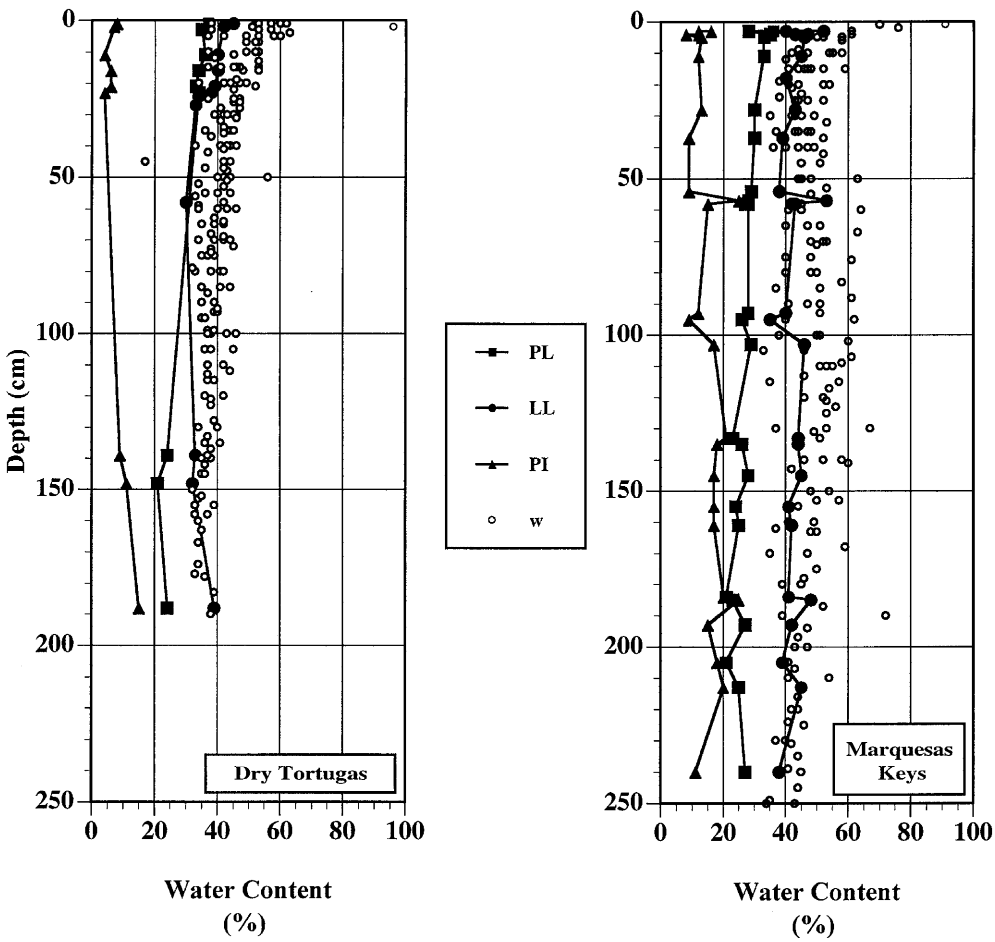

Fig. 6 Water content and Atterberg limit profiles for sediments from the Dry Tortugas Keys and Marquesas Keys study sites

$$\rho_t(\mathrm{g/cm^3}) = 1.68(z)^{0.025} \tag{10}$$

for which $r^2 = 0.424$.

When all data were included to a depth of 300 cm:

$$w(\%) = 54.3(z)^{-0.036} \tag{11}$$

for which $r^2 = 0.082$, and

$$\rho_t(\mathrm{g/cm^3}) = 1.74(z)^{0.009} \tag{12}$$

for which $r^2 = 0.092$. Equations (9) and (10) show modest correlations of w and ρ_t with depth for the upper 50 cm of sediment (Fig. 9). However, when all the data

Table 3 Grain-size data for sediments from the Dry Tortugas Keys and the Marquesas Keys study sites. Grain-size fractions (gravel, sand, silt, clay) based on MIT classification. μ_{mm} Mean grain size (mm); μ_{ϕ} mean grain size (ϕ)

Site	Core	Depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	μ_{mm} (mm)	μ_{ϕ} (ϕ)
Dry Tortugas Keys	KW-SJ-GC-214	40–45	0	52	28	20	0.067	3.90
		80–85	3	52	31	14	0.048	4.37
	KW-SJ-BC-216	0–1	0	44	47	9	0.055	4.18
	KW-SJ-GC-232	47–52	10	67	20	3	0.220	2.17
	KW-SJ-BC-245	6–20	2	42	44	0	0.086	3.54
	KW-SJ-GC-257	0–5	0	47	33	20	0.031	5.04
	KW-SJ-GC-288	30–36	13	51	23	13	0.108	3.21
		124–130	9	21	26	44	0.008	6.96
	KW-SJ-GC-293	55–65	1	36	40	23	0.015	6.06
	KW-SJ-GC-310	45–50	3	51	32	14	0.040	4.64
	KW-SJ-GC-313	9–16	4	68	28	0	0.153	2.70
		22–26	3	63	24	10	0.179	2.47
		30–34	6	68	22	4	0.172	2.53
		80–87	3	73	23	1	0.180	2.47
		108–113	9	73	13	5	0.180	2.47
		135–142	28	60	12	0	0.536	0.88
		183–193	3	72	25	0	0.178	2.48
	KW-SJ-GC-321	41–47	2	60	31	7	0.107	3.23
	KW-SJ-BC-324	0–2	0	67	24	9	0.042	4.58
	Average value:	–	6	56	28	10	–	–
Marquesas Keys	KW-SJ-GC-168	55–60	3	24	52	21	0.014	6.13
	KW-SJ-GC-178	1–6	5	32	50	13	0.041	4.61
		25–32	1	31	42	26	0.010	6.65
		158–163	5	15	43	27	0.008	6.99
		180–187	10	26	34	30	0.006	7.50
		202–207	2	36	34	28	0.009	6.89
	KW-SJ-GC-182	0–10	14	60	25	1	0.313	1.66
		100–106	2	73	25	0	0.165	2.59
		210–216	9	79	12	0	0.335	1.56
	KW-SJ-GC-188	92–108	0	52	45	3	0.060	4.06
	KW-SJ-GC-213	182–188	10	17	48	25	0.021	5.60
	Average value:	–	6	41	37	16	–	–

were included (Eqs. 11 and 12) there was little, if any, correlation (Fig. 10).

Calcium carbonate content values varied between about 85 to 90% with depth (average value of 87% by weight; Fig. 5). Measured values of G_s for Marquesas Keys cores ranged from 2.75 to 2.89 (Table 6; Fig. 5).

Many of the samples from the Marquesas Keys site exhibited some degree of plasticity, and the values were somewhat higher than those documented at the Dry Tortugas Keys site (Table 6). The average values for the PL, LL, and PI were 28, 43 and 15%, respectively (Table 2). The in-situ water contents of these sediments were generally above the liquid limit values (Fig. 6).

Sediments from the Marquesas Keys site have constituents similar to those of the Dry Tortugas Keys site, consisting primarily of sandy silt and clay sediments, with some shell fragments (Table 3). Grain size was relatively constant with depth, and average values of 6% gravel, 41% sand, 37% silt, and 16% clay were determined in the upper 300 cm (Table 3). The combined silt and clay fractions (mud) accounted for 53% of the sediment, as compared with 38% for the Dry Tortugas Keys. The sand contents ranged from 15 to 79% in the upper 300 cm. Table 2 shows that the mean grain size varied from 0.006 mm ($\phi = 7.40$) to 0.335 mm ($\phi = 1.56$), which is somewhat finer than for sediments from the Dry Tortugas Keys site.

There was not much spatial variation of physical and index properties across the Marquesas Keys site, although some variability was recorded with depth within individual cores.

Compressibility and permeability

Consolidation and permeability results from one-dimensional CRD tests for samples from core KW-SJ-GC-178 are shown in Fig. 11 and are summarized in Table 4. The data show that the sediments had C_c values between 0.220 and 0.580, C_r values between 0.010 and 0.03, and they do not show a strong depth dependency. *SSR* values decreased from 4.3 to 1.6 with increasing depth in the upper 90 cm, and indicate slight apparent overconsolidation. The transition from an overconsolidated state to a normally consolidated state occurred at about 180 cm.

Values of permeability at in-situ void ratios were interpolated from measured permeabilities and ranged

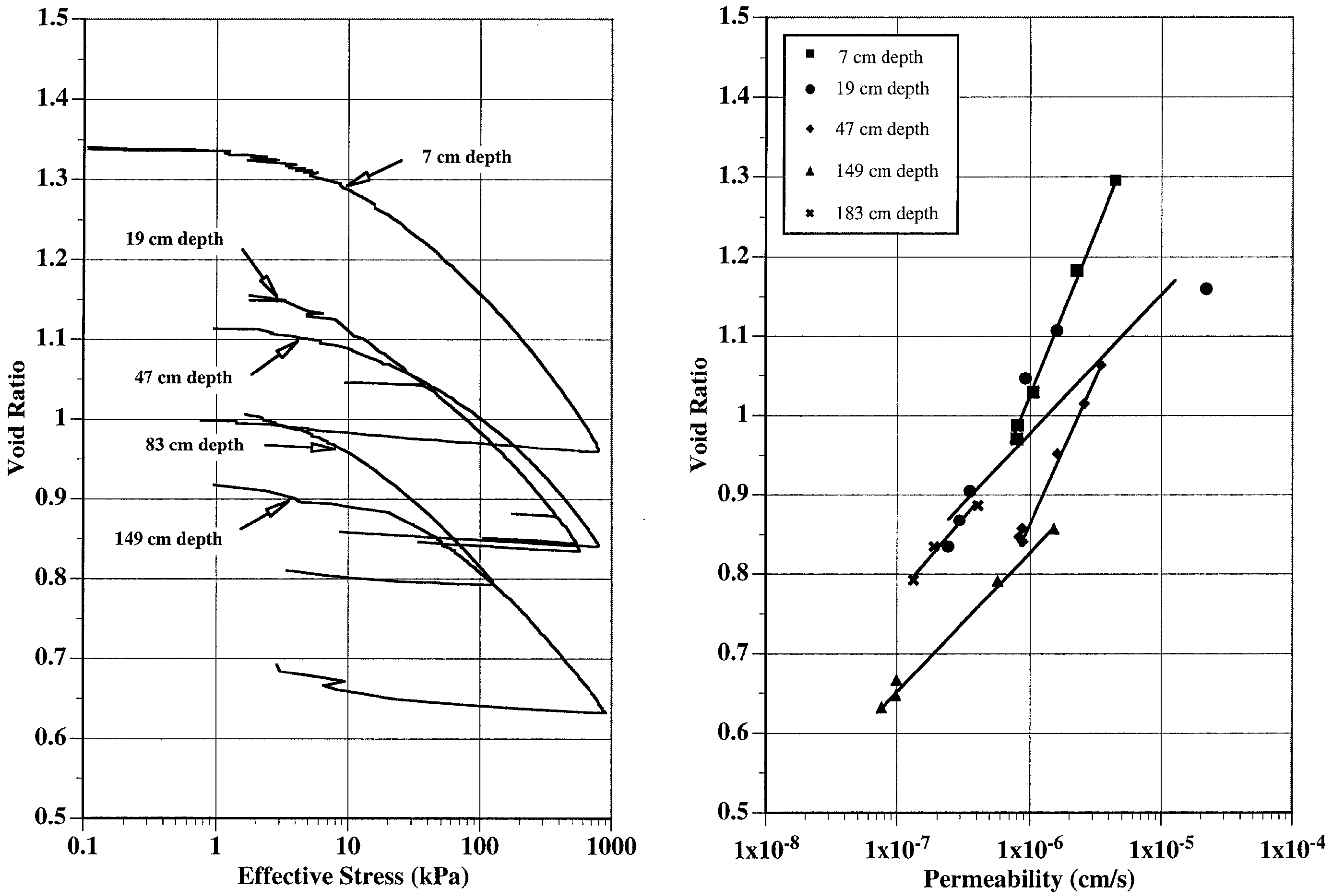

Fig. 7 CRD consolidation and permeability test results for core KW-SJ-GC-313, Dry Tortugas Keys study site

from 1.9×10^{-6} to 7.1×10^{-7} cm/s (Table 4). Permeability values were generally lower than those at the Dry Tortugas Keys site.

Undrained shear strength

In most cores, measurements of s_u were less than about 20 kPa, and the shear strength profile showed a gradual increase with depth (Figs. 9 and 10). This gradual change is in contrast to the marked stiffening of Dry

Table 4 CRD consolidation and permeability test results for sediments from the Dry Tortugas Keys and the Marquesas Keys study sites; *n.d.* not determined

Core	Depth (cm)	w (%)	e_o	C_c	C_r	σ'_p (kPa)	σ'_p (kPa)	SSR	k (at e_o) (cm/s)
Dry Tortugas Keys									
KW-SJ-BC-245	13	49.3	1.358	0.163	0.008	10.0	1.0	10.0	3.40×10^{-6}
KW-SJ-GC-313	7	49.3	1.348	0.250	0.013	30.0	0.5	60.0	5.70×10^{-6}
	19	43.3	1.183	0.145	0.050	38.0	1.3	29.2	2.60×10^{-6}
	47	42.2	1.153	0.230	0.010	72.0	3.6	20.0	6.00×10^{-6}
	83	36.5	0.997	0.170	0.008	130.0	6.6	19.7	7.40×10^{-6}
	149	34.8	0.950	0.205	0.030	64.0	12.3	5.2	5.10×10^{-6}
	149 R	34.7	0.947	0.140	0.010	n.d.	12.3	n.d.	4.40×10^{-7}
	183	37.6	1.028	0.168	0.013	8.5	15.2	0.6	2.20×10^{-6}
KW-SJ-GC-317	87	38.1	1.043	0.104	0.005	13.0	6.5	2.0	2.00×10^{-5}
	186	36.5	0.992	0.100	n.d	34.0	14.8	2.3	1.70×10^{-6}
KW-SJ-GC-321	129	38.7	1.043	0.228	0.008	38.0	10.6	3.6	1.30×10^{-4}
Marquesas Keys									
KW-SJ-GC-178	13.5	43.9	1.199	0.220	0.020	4.3	1.0	4.3	n.d.
	28.5	52.3	1.445	0.340	n.d.	7.0	2.1	3.3	1.30×10^{-6}
	57.5	62.8	1.716	0.490	0.020	10.0	4.1	2.4	8.00×10^{-7}
	84.5	58.8	1.607	0.580	0.035	9.5	5.9	1.6	1.30×10^{-6}
	183.5	52.6	1.438	0.295	0.010	11.0	13.0	0.9	1.90×10^{-6}
	210.5	46.0	1.257	0.247	0.020	12.0	15.0	0.8	7.10×10^{-7}

Table 5 CIU triaxial compression strength test results for sediments from the Dry Tortugas Keys study site (Pizzimenti 1996; Pizzimenti and Silva 1997). U = Undisturbed sample; R = remolded sample; ε_f = axial compressive strain. $A_f = (\Delta u_d)_f/(\Delta\sigma_d)_f$; $(\Delta\sigma_d)_f$ = Deviator stress; $(\Delta u_d)_f$ = pore pressure due to deviator stress. Subscript f indicates parameter value at the failure condition; *n.d.* not determined

Core	Depth (cm)	e	p'_o (kPa)	ε_f (%)	(σ'_1/σ'_3)	$\Delta\sigma'_f$ (kPa)	$\Delta u'_f$ (kPa)	A_f	E_i (kPa)
KW-SJ-BC-284	2–13 U	1.20	31.7	11.6	3.9	51.4	13.9	0.27	n.d.
	2–15 R	1.00	34.0	11.8	4.3	58.0	19.2	0.33	18,873
	2–13 U	1.10	16.0	12.7	3.9	28.6	6.3	0.22	6,077
	2–17 R	1.30	13.9	11.6	4.0	13.9	7.0	0.50	6,981
	2–13 U	1.10	15.0	10.5	4.4	21.7	8.4	0.39	4,444
	2–13 R	1.10	16.5	11.4	4.4	32.3	7.3	0.23	n.d.
	3–14 U	1.20	2.4	6.9	5.9	9.2	0.5	0.05	2,077
	3–16 R	1.20	2.2	11.9	6.1	3.3	1.5	0.39	530
	9–11 R	1.00	1.8	11.1	8.4	6.6	0.9	0.14	650
KW-SJ-BC-324	1–12 U	1.30	29.6	11.7	4.4	34.0	19.5	0.57	11,125
	1–14 R	1.20	28.2	13.0	3.9	25.5	19.1	0.75	12,444
	1–12 U	1.30	10.5	11.7	4.3	18.4	5.0	0.27	3,988
	0–15 R	1.20	10.0	11.0	4.8	20.0	4.8	0.24	3,879
	3–14 U	1.30	8.3	9.2	4.2	17.6	2.7	0.15	2,397
	3–17 R	1.20	6.2	17.2	4.1	11.7	2.5	0.021	n.d.
	2–13 U	1.40	1.5	14.0	5.8	3.7	0.7	0.19	130
	0–13 R	1.40	1.2	20.5	40.0	2.7	1.2	0.44	166

Table 6 Specific gravity and Atterberg limits values for sediments from the Marquesas Keys study site (all specific gravity and Atterberg limit values are corrected for 35-ppt salt content). *n.d.* Not determined. *NP* Nonplastic

Core	Depth (cm)	G_s	PL (%)	LL (%)
KW-SJ-GC-166	4	2.83	35	43
	23	2.82	n.d.	n.d.
	37	n.d.	30	39
	58	2.84	27	42
	95	n.d.	26	35
	155	2.89	24	41
KW-SJ-GC-178	4	2.79	35	47
	29	2.76	n.d.	n.d.
	57	2.83	28	53
	161	2.76	25	42
	184	2.81	21	41
	205	2.83	21	39
KW-SJ-GC-182	5	2.79	33	46
	28	n.d.	30	43
	58	2.80	28	43
	103	2.80	29	44
	145	2.75	28	45
	213	2.78	25	45
KW-SJ-GC-192	4	n.d.	NP	n.d.
	18	n.d.	NP	40
	54	n.d.	29	38
	93	n.d.	28	40
	135	n.d.	26	44
	193	n.d.	27	42
	240	n.d.	27	38
KW-SJ-GC-199	3	n.d.	28	40
KW-SJ-BC-211	3	n.d.	36	52
	11	n.d.	33	45
KW-SJ-GC-213	64	2.81	n.d.	n.d.
	133	2.81	23	46
	185	2.79	23	48
	276	2.80	n.d.	n.d.

Tortugas Keys sediments with depth. The variation of s_u with z for the upper 50 cm at the Marquesas Keys site can be approximated as:

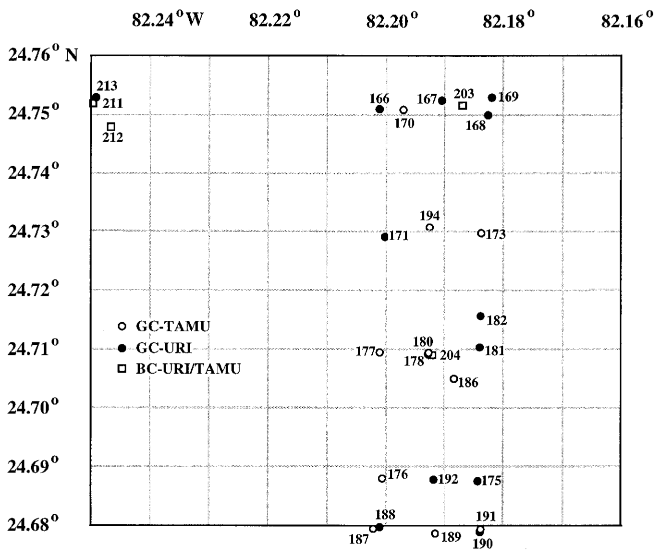

Fig. 8 Core locations at the Marquesas Keys study site

$$s_u(\text{kPa}) = 1.45(z)^{0.468} \quad (13)$$

for which $r^2 = 0.352$, and when all data are included to a depth of 300 cm:

$$s_u(\text{kPa}) = 2.27(z)^{0.294} \quad (14)$$

for which $r^2 = 0.225$. Equation (13) represents a somewhat better fit for the s_u data with z in the upper 50 cm than Eq. (14) for all depths down to 300 cm. The coefficients of determination were rather low for both equations compared with the corresponding equations (Eqs. 6 and 7, respectively) for the Dry Tortugas site. As was the case for the Dry Tortugas Keys sediments, a direct relationship between w and s_u was not evident.

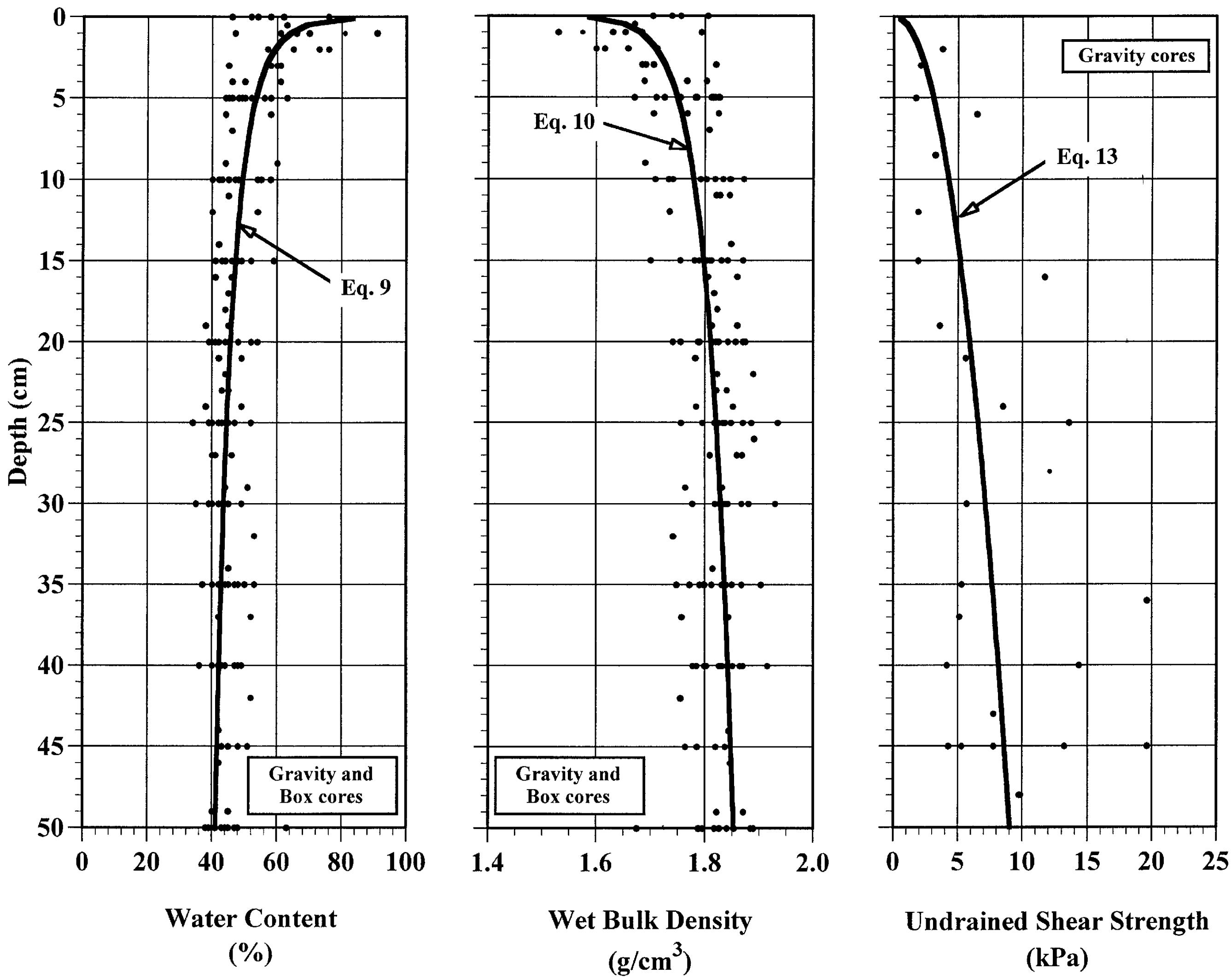

Fig. 9 Water content, wet bulk density, and shear strength profiles for sediments from die Marquesas Keys study site (upper 50 cm)

MSCL measurements

MSCL results for geoacoustic properties of sediments from the Dry Tortugas Keys and the Marquesas Keys study sites show that most cores exhibited strong relationships between ρ_t (determined from water content measurements and gamma ray attenuation) and acoustic response (Figs. 12 and 13). Increases in ρ_t were generally associated with increases in compressional wave velocity and impedance, and with decreases in attenuation. For the Dry Tortugas Keys sediments, compressional wave velocities averaged between 1,475 and 1,650 m/s. In general, ρ_t increased with depth for each core, with the most prominent increase in the upper 25 cm of the sediment column. Compressional wave velocity values averaged between 1,450 and 1,590 m/s for the Marquesas Keys sediments. Generally, ρ_t increased with depth for each core, with the most prominent increase occurring in the upper 20 cm of the sediment column. The presence of shells and shell fragments at various depths typically led to lower compressional wave velocities in these sections.

Discussion

The sediments at the Dry Tortugas Keys are derived from a low- to moderate-energy depositional basin and the site is well protected from the prevailing weather (Richardson et al. 1997). At the eastern and southern ends of the site the sediments were markedly coarser and denser due, in part, to the more dynamic water column present there than at other areas of the site. Sediments were finer at the northern and western edges of the site, which is a low energy environment better protected from winds and currents, and therefore with larger proportions of sand, silt, and clay. The Marquesas Keys site is hydrodynamically more active, being in open water, and is subjected to reworking of the seabed by frequent storms, strong tidal currents, and other active processes (Briggs and Richardson 1997). Generally, a more uniform depositional environment exists, with sediments

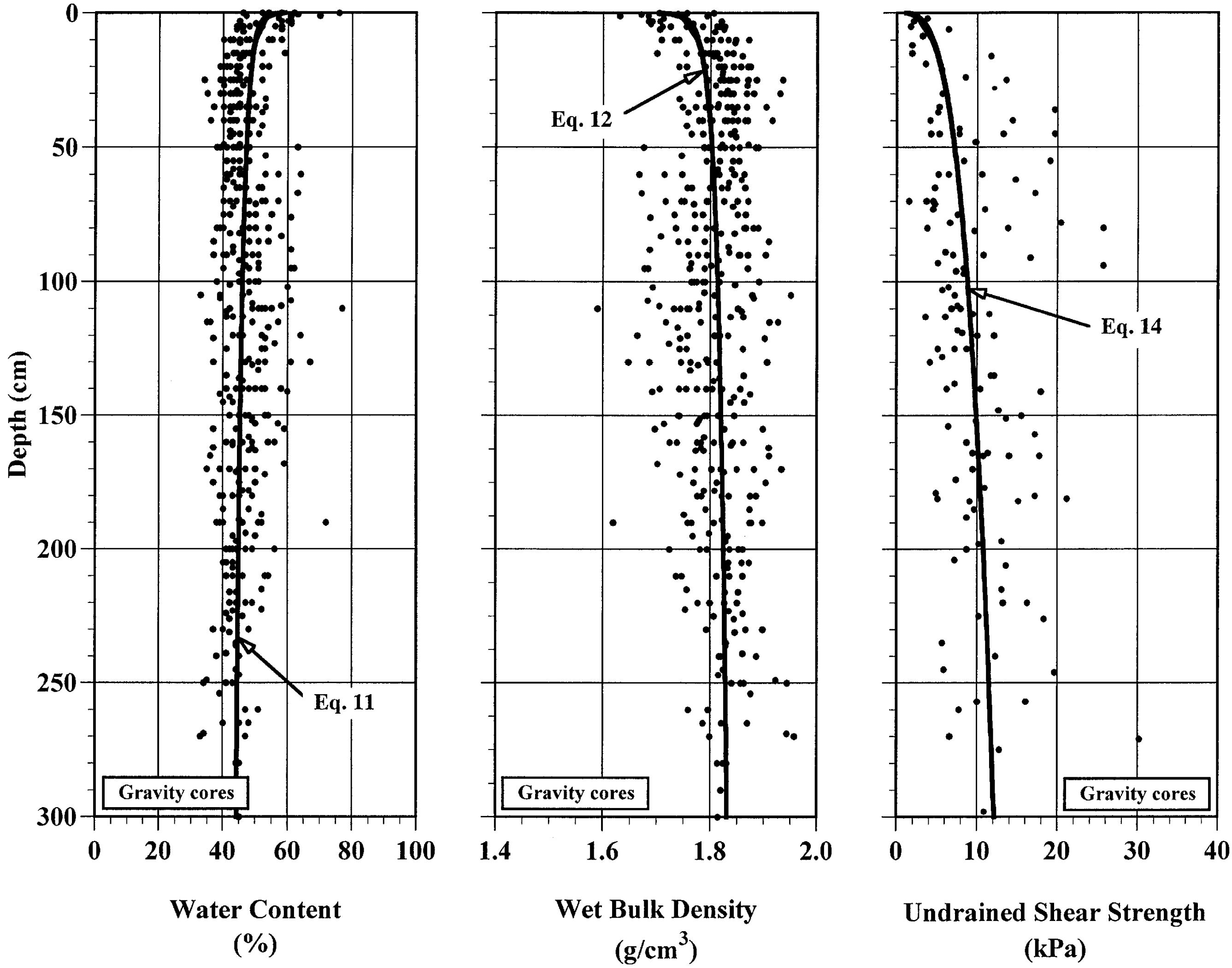

Fig. 10 Water content, wet bulk density, and shear strength profiles for sediments from the Marquesas Keys study site (upper 300 cm)

becoming progressively finer in the northerly directions (Richardson et al. 1997).

Sediments from the Marquesas Keys site have constituents similar to those at the Dry Tortugas Keys site. However, larger portions of fine-grained sandy silt and clay-size materials were evidenced, with smaller amounts of coarse sand and shell fragments. There was more spatial variation in physical and index properties across the Dry Tortugas Keys site than at the Marquesas Keys, due to differences in depositional and environmental characteristics which exist across the Dry Tortugas Keys study area.

At the Marquesas Keys site, wet bulk density values were generally lower (1.80 g/cm^3) in the top 25 cm compared with the Dry Tortugas Keys site. However, values of ρ_t for the Marquesas Keys sediments were also lower at depths below 25 cm, due to the more open structure of the finer sediments at this site. Most of the Marquesas Keys cores showed considerable fine-scale (1 cm) as well as large-scale (on the order of 100 cm) wet bulk density variations, some of which are presumably related to the relative abundance of pockets of shell clusters.

The high carbonate contents for the Dry Tortugas Keys (93%) and Marquesas Keys (85% to 90%) sediments are indicative of carbonate sands which exhibit granular behavior, an interpretation which was confirmed by the laboratory testing program. Calcium carbonate content values for sediments from both sites are consistent with published data (Lide 1994) for calcium carbonate minerals, including calcite (2.71) and aragonite (2.95). Dry Tortugas Keys sediments are low plasticity clayey silts and are classified as ML based on the Unified Soil Classification System (ASTM 1994). The Marquesas Keys sediments are generally sandy silts and low plasticity clays, which are classified as ML and CL, respectively. The finding that most of the Dry Tortugas Keys sediment samples showed little or no plasticity, whereas most of the Marquesas Keys sediments showed a low degree of plasticity is consistent with the lower calcium carbonate contents and larger proportions of fine material at the Marquesas Keys site. Reductions in Atterberg limit values with increases in carbonate

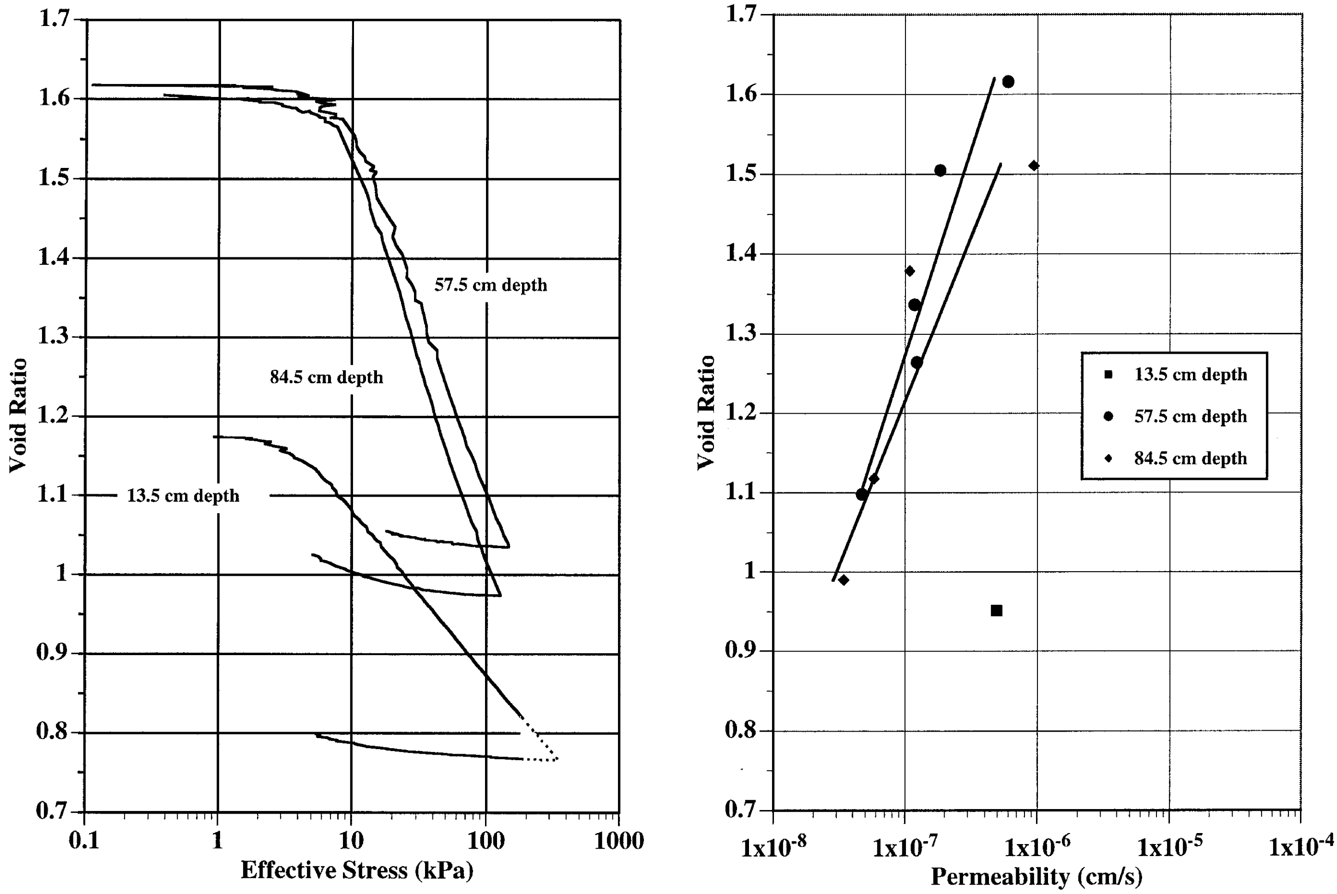

Fig. 11 CRD consolidation and permeability test results for core KW-SJ-GC-178, Marquesas Keys study site

content have been also observed by other researchers (Nacci et al. 1975; Demars et al. 1976).

CRD consolidation test results indicate apparent overconsolidation ($SSR > 1.0$) in undisturbed sediment samples, which was particularly strong ($SSR > 7.5$) in the surficial (upper 50 cm) sediments from the Dry Tortugas Keys site. *SSR* values greater than unity suggest that strong interparticle bonds were present. At the Dry Tortugas Keys site, *SSR* values decreased from 60 to 5.2 with increasing depth in the upper 300 cm. This is common in surficial (upper few meters) ocean sediments, especially fine-grained marine sediments, and can be attributed to cementation and/or interparticle bonding (Silva and Jordan 1984). The transition from an overconsolidated ($SSR > 1.0$) to a normally consolidated condition ($SSR = 1.0$) in clayey sediments is usually defined by a sharp, well-defined break in the consolidation curve. The gradual change in slope observed in the CRD consolidation data is indicative of granular sediment behavior. *SSR* values trended toward a normally consolidated state with depth, which is typical for increasing effective stresses. The Dry Tortugas Keys sediments are relatively sandy and stiff, which is primarily due to the high carbonate contents and relatively large grain sizes.

Sediments from the Marquesas Keys site were more compressible than those from the Dry Tortugas Keys site, as evidenced by the higher C_c values. This can be attributed to the slightly lower calcium carbonate contents, larger proportions of fines, and the lower wet bulk densities of the Marquesas Keys sediments. *SSR* values decreased from 4.3 to 1.6 with increasing depth in the upper 90 cm. The transition from an overconsolidated state to a normally consolidated state occurred at about 180 cm. This change with depth is typical of several marine sedimentary regimes (Silva and Jordan 1984). The apparent overconsolidation of the Marquesas Keys sediments implies possible light cementation and/or interparticle bonding associated with surficial sediments at this study site. As with the Dry Tortugas Keys sediments, the lack of a well-defined transition in the Marquesas Keys consolidation data indicates granular sediment behavior.

Permeability values for the Dry Tortugas Keys sediments are typical of silty sands and silts, whereas those for the Marquesas Keys sediments are typical of silts (Lambe and Whitman 1969). Sediments from the Marquesas Keys site generally had lower k values than those from the Dry Tortugas Keys site, due to a relatively larger proportion of fine-grained sediment. CRD test results generally indicated a decrease in k with increasing overburden pressure and a decrease in void ratio (Figs. 7 and 11). Results from a CRD test of a

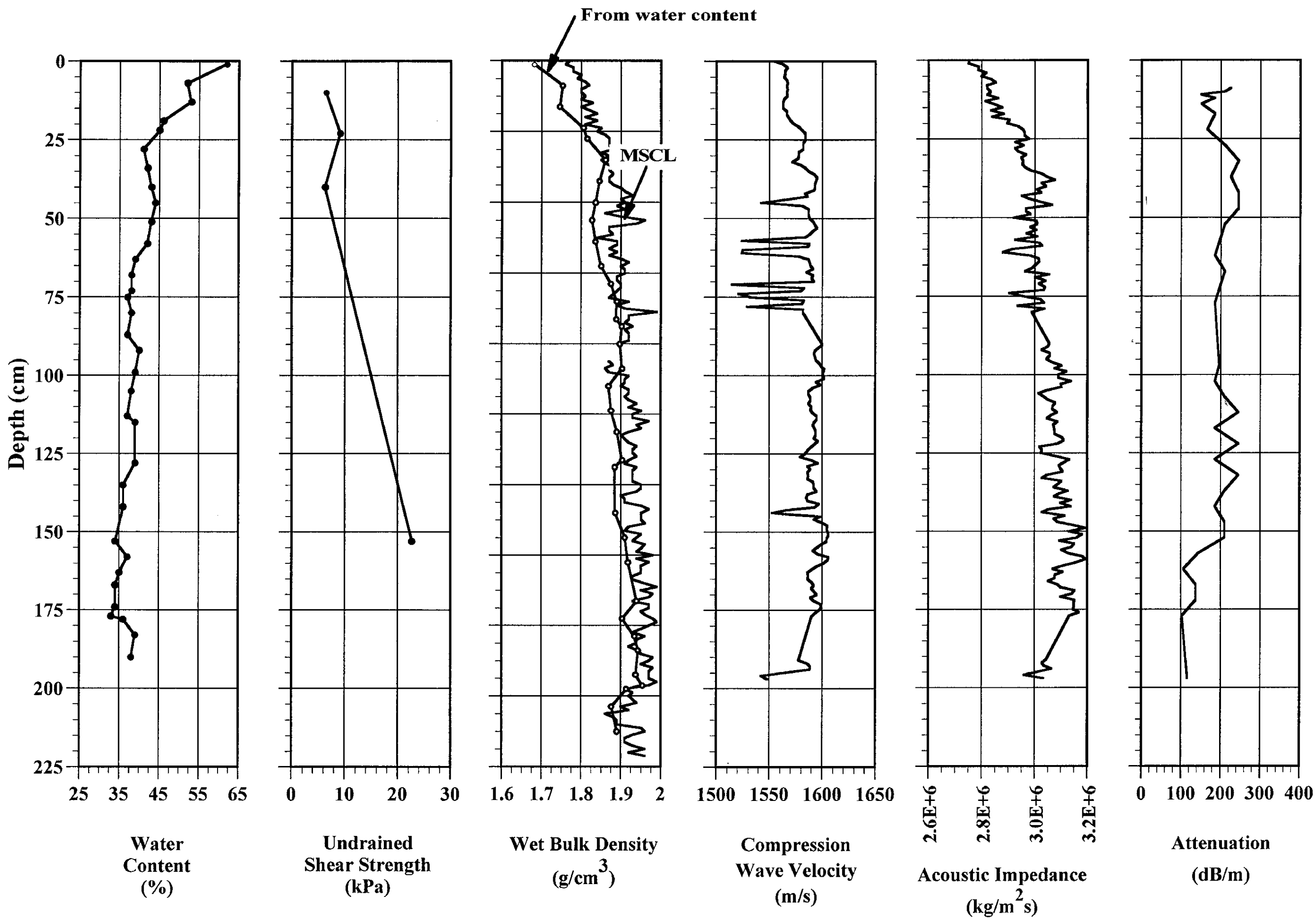

Fig. 12 Typical physical and acoustic profiles from core KW-SJ-GC-313, Dry Tortugas Keys study site

remolded sample of Dry Tortugas Keys sediment (depth 149-R, Table 4) indicated about an order of magnitude reduction in k and reductions in the values of C_c and C_r. These results imply that the remolding process tends to result in a stiffer, less permeable sediment structure, most likely due to a more even distribution of finer grained particles.

Undrained shear strength profiles for Dry Tortugas Keys sediments (Figs. 3 and 4) indicate a marked stiffening with depth, which can be attributed to increasing overburden stresses, increasing wet bulk density, and possibly some cementation or other physicochemical processes. Sharp peaks observed in some of the shear strength profiles may at least partly be due to shell fragments encountered by the vane, although attempts were made to avoid shells whenever possible. Scatter observed in the data also suggests spatial variability of undrained shear strength across the site. The lack of any obvious relationship between w and s_u is to be expected for granular materials, whose strength depends on density, grain size, grain shape, and effective confining pressure.

CIU triaxial strength test results did not indicate signs of brittle behavior, which is typically characteristic of cemented calcareous sediments (Clough et al. 1981). However, the results do suggest that shear strength is derived from particle interlocking and interparticle friction as strength mechanisms (Pizzimenti 1996). The results of the CIU tests and Eq. (8) indicate that the behavior of this carbonate sediment is similar to that of a loose to moderately dense uncemented sand. Strength results are similar to those reported by other researchers who have studied calcareous deposits (Datta et al. 1979, 1981; Poulos 1990) and are comparable to those of uncemented silica sands at the same density (Lambe and Whitman 1969).

Undrained shear strength profiles for the Marquesas Keys sediments showed a gradual increase with depth (Figs. 9 and 10), which is in contrast to the marked stiffening of Dry Tortugas Keys sediments with depth. This can be attributed to the finer sediments, lower wet bulk densities, and normal densification from increasing overburden pressures at the Marquesas Keys site. Shear strength results indicate soft to medium stiff sediments, suggest little or no cementation, and generally had greater variation in s_u with depth than for sediments from the Dry Tortugas Keys site. There does not appear to be any direct relationship between w and s_u for these sediments, as was also the case for the Dry Tortugas Keys sediments.

MSCL measurements of compressional wave velocities showed that the presence of shells and shell

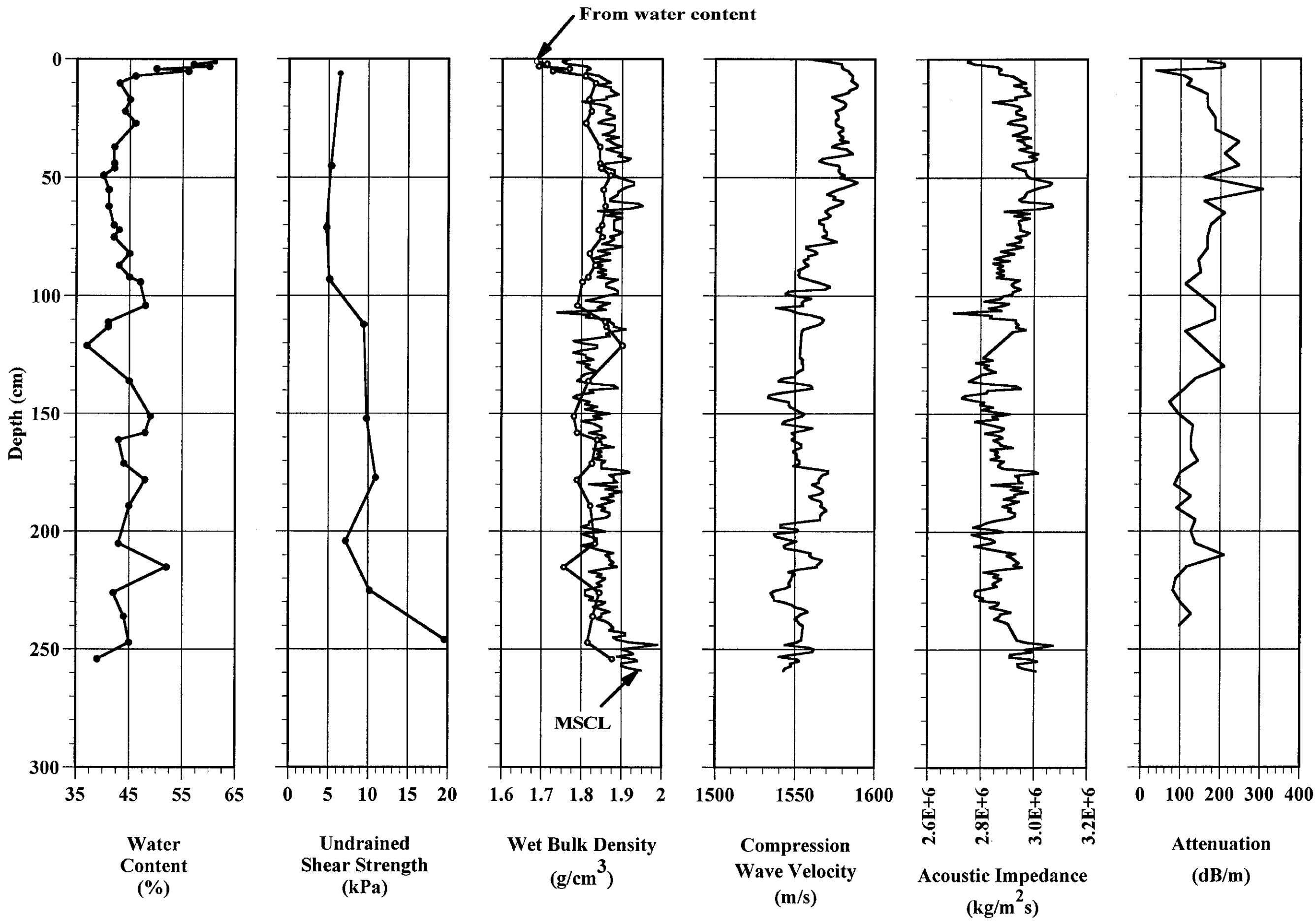

Fig. 13 Typical physical and acoustic profiles from core KW-Si-GC-178, Marquesas Keys study site

fragments typically tended to reduce wave velocities. This effect was investigated at the MGL in detail by Sykora (1998), who studied the influence of shell content on the geoacoustic behavior of sediments from the Dry Tortugas Keys, and found that a decrease in compressional wave velocity occurs with increasing amounts of shell material. Sykora (1998) also tested the shear strength remolded Dry Tortugas Keys sediment samples and observed that the destruction of bonds associated with shearing resulted in a decrease in interparticle contacts, which lead to loss of acoustic energy and a reduction in compressional wave velocity.

The data collected in this study provide useful insight into the nature and behavior of the carbonate sediments found at the Lower Florida Keys study sites. Differences in depositional and environmental characteristics exist across the Dry Tortugas Keys study site, and between the Dry Tortugas Keys and Marquesas Keys sites. These differences are major factors in determining the sediment types found at each site, and their geotechnical and acoustic characteristics. The results obtained from this study should be considered along with those obtained by other researchers who also conducted investigations as a part of the CBBL SRP. Integration of the results obtained from all of these studies will be very beneficial for gaining a more complete understanding of the geotechnical characteristics of the Dry Tortugas Keys and Marquesas Keys study sites.

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References

Ag A (1994) Consolidation and permeability behavior of high porosity Baltic seabed sediments. MSc Thesis, Department of Ocean Engineering, University of Rhode Island, Kingston, RI

ASTM (1994) Annual book of ASTM standards, vol 04.08. Soil and rock I. American Society for Testing and Materials, Philadelphia, PA

Brandes HG, Silva AJ, Ag A, Veyera GE (1996) Consolidation and permeability characteristics of high porosity surficial sediments in Eckernförde Bay. Geo-Mar Lett 16:175–181

Briggs KB, Richardson MD (1997) Small scale fluctuations in acoustic and physical properties in surficial carbonate sediments and their relationship to bioturbation. Geo-Mar Lett 17:306–315

Brogan DA (1995) Stress-strain behavior of low shear strength sediments from the Baltic Sea. MSc Thesis, Department of Ocean Engineering, University of Rhode Island, Kingston, RI

Clough GW, Sitar N, Bachus RC, Rad NS (1981) Cemented sands under static loading. J Geotech Eng, ASCE 107(GT6):799–817
Datta M, Gulhati SK, Rao GV (1979) Crushing of calcareous sand during shear. In: Proc 10th Offshore Technology Conf, Houston, TX, April, pp 345–351
Datta M, Rao GV, Gulhati SK (1981) The nature and engineering behavior of carbonate soils at Bombay High, India. Mar Geotechnol 4(4):307–341
Datta M, Rao GV, Gulhati SK (1982) Engineering behavior of carbonate soils of India and some observations of classification of such soils. In: Geotechnical properties, behavior and performance of carbonate soils. ASTM STP 777, pp 113–140
Davis A, Huws D, Haynes R, Bennell J (1995) Geophysical sea floor sensing in a carbonate sediment regime. In: 1st SEPM Congr Sedimentary Geology, St. Pete Beach, FL, pp 43–44
Demars KR, Nacci VA, Kelly WE (1976) Carbonate content: an index property for ocean sediments. In: Proc 8th Offshore Technology Conf, Houston, TX, pp 97–105
Folk RL (1974) Petrology of sedimentary rock. Hamphill, Austin, TX
Janbu N (1963) Soil compressibility as determined by oedometer and triaxial tests. In: European Conf Soil Mechanics and Foundation Engineering, Weisbaden, vol 1, pp 19–25
Kondner RL (1963) Hyperbolic stress-strain response: cohesive soils. J Soil Mech Foundations Div, ASCE 89(SM1):115–143
Lambe TW, Whitman RV (1969) Soil mechanics. Wiley, New York
Lavoie DL, Richardson MD, Holmes C (1997) Benthic boundary layer processes in the Lower Florida Keys. Geo-Mar Lett 17:232–236
Lide DR (1994) CRC handbook of chemistry and physics, 74th edn. CRC Press, Boca Raton, FL
Mitchell JK (1993) Soil behavior. Wiley, New York
Nacci VA, Wang MC, Demars KR (1975) Engineering behavior of calcareous soils. In: Proc Civil Engineering in the Oceans, ASCE, Newark, DE, pp 380–400
Noorany I (1982) Friction of calcareous sand. Rep N62583-81MR647, Civil Engineering Laboratory, Naval Construction Engineering Battalion Center, Port Hueneme, CA
Pizzimenti PB (1996) Stress-strain behavior of surficial carbonate sediments from Key West, Florida. MSc Thesis, Department of Ocean Engineering, University of Rhode Island, Kingston, RI
Pizzimenti PB, Silva AJ (1997) Stress-strain behavior of surficial carbonate sediments from Key West, Florida, USA. Mar Geores Geotechnol 15:335–362
Poulos HG (1990) A review of the behavior and engineering properties of carbonate soils. In: Engineering properties of calcareous sediments. Center for Geotechnical Research University of Sydney Bull GB5, Pap No 2, pp 17–27
Poulos HG, Chua EW, Hull TW (1984) Settlement of model footings on calcareous sand. J Geotech Eng Div, ASCE 100(GT10):21–35
Richardson MD, Lavoie DL, Briggs KB (1997) Geoacoustic and physical properties of carbonate sediments of the Lower Florida Keys. Geo-Mar Lett 17:316–324
Schulteiss PJ, Weaver PPE (1992) Multi-sensor core logging for science and industry. J IEEE 7:608–613
Semple RM (1988) The mechanical properties of carbonate soils. In: Proc Int Conf Calcareous Sediments, ISSMFE, Perth, vol 2, pp 807–836
Silva AJ, Brandes HG (1995) Cruise report, Key West campaign, coastal benthic boundary layer special research program. Marine Geomechanics Laboratory, University of Rhode Island, Kingston, RI
Silva AJ, Jordan SA (1984) Consolidation properties and stress history of some deep sea sediments. In: Proc IUTAM and IUGG Symp Seabed Mechanics, London, pp 25–40
Sykora GF (1998) Acoustic characteristics in relation to stress-strain behavior of calcareous sediments from Key West, Florida. MSc Thesis, Department of Ocean Engineering, University of Rhode Island, Kingston, RI
Valent PJ, Altschaeffl AG, Lee HJ (1982) Geotechnical properties of two calcareous oozes. In: Geotechnical properties, behavior, and performance of calcareous soils. ASTM STP 777, pp 79–96
Wikar KC (1993) Development of constant flow triaxial compression system for marine sediments. MSc Thesis, Department of Ocean Engineering, University of Rhode Island, Kingston, RI