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ACOUSTIC RETRIEVAL OF SEAFLOOR GEOTECHNICS.(U)
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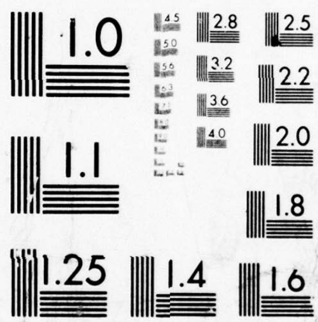

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Technical Note

CEL

TN no. N-1513

title: ACOUSTIC RETRIEVAL OF SEAFLOOR GEOTECHNICS

author: Homa Lee and R. J. Malloy

date: December 1977

sponsor: Naval Facilities Engineering Command

program nos: YF52.556.091.01.109

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

ACKNOWLEDGMENTS

The constructive guidance and suggestions of Mr. Phil J. Valent and assistance with the computer analyses by Zaher Gouda are gratefully acknowledged.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(14) **REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TN-1513 CEL-TN-1513

2. GOVT ACCESSION NO: DN 787010

3. RECIPIENT'S CATALOG NUMBER: (9) Technical note Oct 76-Sep 77

4. TITLE (and Subtitle): (6) ACOUSTIC RETRIEVAL OF SEAFLOOR GEOTECHNICS.

5. TYPE OF REPORT & PERIOD COVERED: Not final; Oct 1976 – Sep 1977

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): (10) Homa/Lee [redacted] R. J./Malloy

8. CONTRACT OR GRANT NUMBER(s): (16) F52556 (17) YF52556091

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Civil Engineering Laboratory
Naval Construction Battalion Center
Port Hueneme, California 93043

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
62759N
YF52.556.091.01.109

11. CONTROLLING OFFICE NAME AND ADDRESS:
Naval Facilities Engineering Command
Alexandria, Virginia 22332

12. REPORT DATE: (11) Dec[redacted]77

13. NUMBER OF PAGES: 33

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): Unclassified (12) 32p.

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Geotechnical properties, seafloor surveying, seafloor construction, foundations, soil properties, underwater soil sampling, acoustic seafloor profiling, site selection, coring.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Acoustic profiling is a rapid and relatively economical means of obtaining considerable information about large areas of the seafloor. Acoustic data can be quantified, and basic theory suggests that these data incorporate seafloor physical parameters similar to those used by geotechnical engineers in foundation and anchor design. This report summarizes the basic acoustic reflection theories and reviews earlier field efforts to quantitatively

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391 111

20. Continued

classify the seafloor with acoustics. It appears that sediment density can be measured with an accuracy range of about ±10%. This in turn leads to sediment classification into at least two categories: sand and clay. Experiments to date have not had sufficient control of physical sampling relative to acoustic testing, and greater accuracies may be possible. The potential for indirectly measuring shear wave velocity and directly inferring shear strength is explored and rejected for the short term. Shear information is contained in acoustic data but is too small to be measured. Shear strength can, in many cases, be deduced from acoustically measured density data, if a few cores are available for calibration. Further work is recommended to determine the true accuracy of acoustic measurements and to develop quantitative acoustic systems to satisfy Navy needs in seafloor geotechnical engineering.

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Civil Engineering Laboratory
ACOUSTIC RETRIEVAL OF SEAFLOOR GEOTECHNICS,
by Homa Lee and R. J. Malloy
TN-1513 33 pp illus December 1977 Unclassified

1. Acoustic seafloor profiling 2. Site selection I. YF52.556.091.01.109

Acoustic profiling is a rapid and relatively economical means of obtaining considerable information about large areas of the seafloor. Acoustic data can be quantified, and basic theory suggests that these data incorporate seafloor physical parameters similar to those used by geotechnical engineers in foundation and anchor design. This report summarizes the basic acoustic reflection theories and reviews earlier field efforts to quantitatively classify the seafloor with acoustics. It appears that sediment density can be measured with an accuracy range of about ±10%. This in turn leads to sediment classification into at least two categories: sand and clay. Experiments to date have not had sufficient control of physical sampling relative to acoustic testing, and greater accuracies may be possible. The potential for indirectly measuring shear wave velocity and directly inferring shear strength is explored and rejected for the short term. Shear information is contained in acoustic data but is too small to be measured. Shear strength can, in many cases, be deduced from acoustically measured density data, if a few cores are available for calibration. Further work is recommended to determine the true accuracy of acoustic measurements and to develop quantitative acoustic systems to satisfy Navy needs in seafloor geotechnical engineering.

CONTENTS

INTRODUCTION

To site, design, and predict the performance of seafloor facilities, some knowledge of the geotechnical properties (strength, compressibility, stiffness) of the bottom sediments is necessary. The level of accuracy needed varies greatly, depending on the importance and size of the facility and on whether siting, preliminary design, or final design is involved. Also, the amount of areal coverage required varies with the same items.

For final design of important structures, the geotechnical properties at a specific site must be known quite accurately (e.g., strength within ±15%). The Civil Engineering Laboratory has explored several procedures to supply the information needed.

CEL, in its research for the ideal technique, developed a method for obtaining piston core samples and correcting for sampling disturbance (Lee, 1973).* The cost of obtaining this information is relatively high, however. In addition, obtaining coverage over an area or along a route is difficult.

For other than final design of important structures, applications (such as siting, preliminary design of less important structures, and cable burial), the geotechnical data need not be as accurate, but large areal coverage may be required. The Expendable Doppler Penetrometer* was developed, in part, to satisfy this need. With this instrument, rapid, relatively accurate (±30%) measurements of sediment strength can be made under almost any sea conditions. Still, the penetrometers provide only point measurements.

A technique for site and route surveying that provides continuous geotechnical data from an underway vessel could greatly augment penetrometer and coring data and reduce overall cost. Acoustic reflection techniques are obvious candidates.

A great deal is known about the way in which acoustic waves reflect from the seafloor and subbottom layer interfaces (e.g., Hastrup,1969; Mackenzie, 1960; Bell and Porter, 1974). It is known that the physical properties that control acoustic reflection (density, bulk modulus, rigidity) are similar to those that control engineering behavior. The major difference is that the strain level developed by acoustic wave transmission and reflection is several orders of magnitude below that for full strength development. Since the controlling properties are basically the same, however, correlations between the two have been found.

Because of the ideal, rapid nature of acoustic profiling and the apparent potential tie-in to geotechnical engineering, CEL conducted a study to determine

*Further work is currently in process and further information can be obtained by contacting H. Lee of CEL.

**For further information, contact R. Beard of CEL.

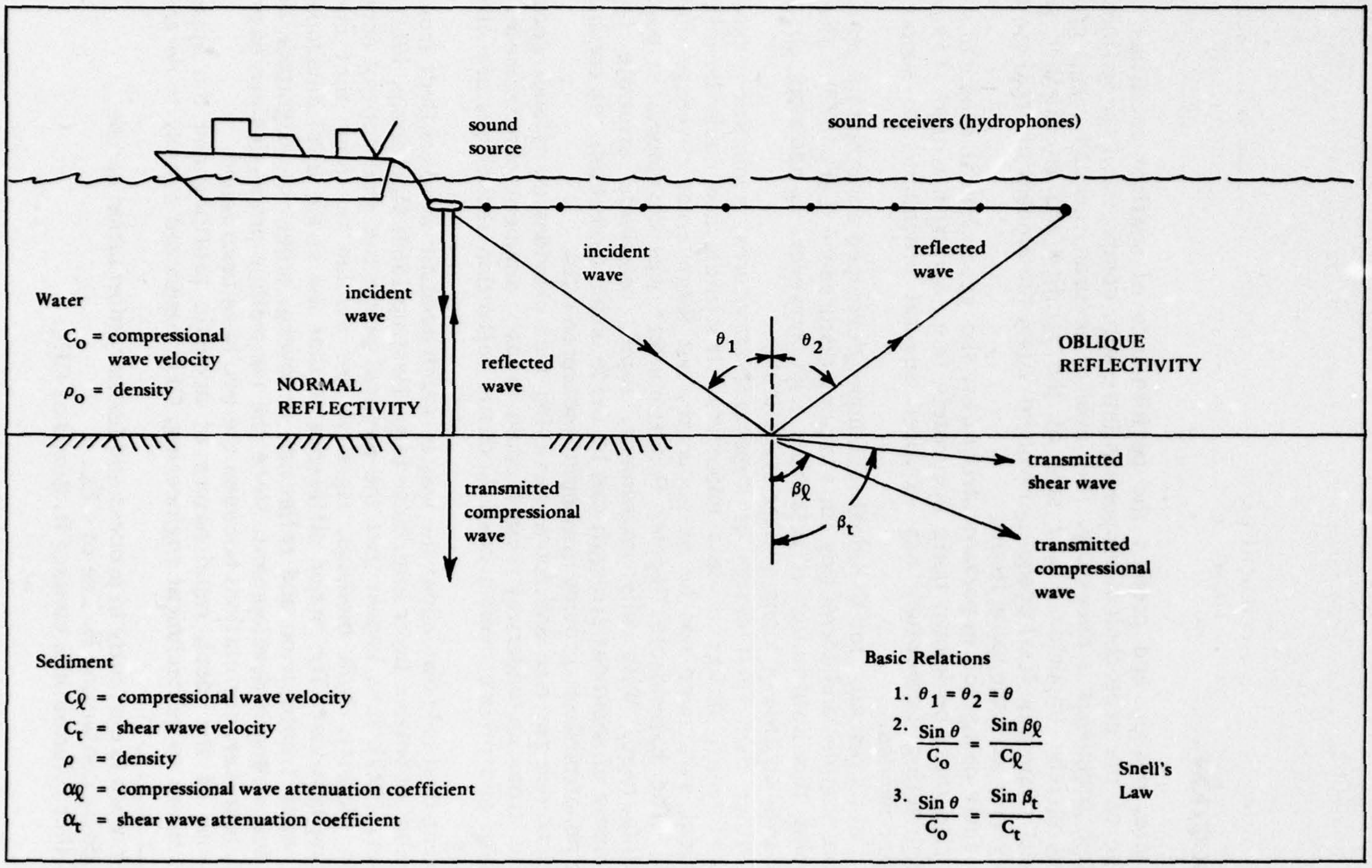

Figure 1. Diagram illustrating basic definitions and concepts.

the applicability of acoustics to geotechnics. First, the current state-of-the-art of acoustic reflection profiling was assessed to determine how well acoustic parameters can presently be measured from an underway vessel. Next, it was determined how well geotechnical parameters could be estimated if the acoustic parameters were known. These led to immediate use recommendations and indicated areas where additional research might improve the quality of the estimates. Finally, a program of research to develop improved estimates was developed. This report summarizes the findings of this study.

It should be noted at this point that acoustics are not expected to solve all the problems of marine geotechnology. For final design, coring and detailed laboratory analysis are expected to remain as requirements. Even for site and route surveys it will generally be necessary to obtain at least a few cores or perform a few penetrometer drops. These are needed because acoustics are not foolproof, and the geotechnical engineer must have a few direct measurements for proper analysis of the acoustic data.

DEFINITIONS AND THEORY

This section provides the nomenclature and basic theory needed to understand the rest of the report.

Definitions

Acoustic Reflection. When a propagating sound wave encounters an interface between materials of differing acoustic impedance (defined below) some energy is reflected while some is transmitted. Normal Reflection implies that the direction of sound propagation is normal to the interface; the transmitted sound continues in the same direction while the reflected sound is returned along its original course. Oblique Reflection implies that the direction of propagation is other than normal to the interface. The direction of propagation of the transmitted wave obeys Snell's Law (law of refraction). Also, the angle of reflection equals the angle of incidence (see Figure 1 for graphic definitions of these concepts). When oblique reflection occurs at a liquid-solid interface, two types of waves - compressional and shear - are set up in the solid. Both obey Snell's Law.

Acoustic Reflectivity, R. The amplitude of the obliquely or normally reflected wave divided by the amplitude of the incident wave is termed the acoustic reflectivity of the interface. There may also be a phase shift, ϕ, or change in wave shape. The most recognizable phase shift is $\phi = 180$ deg, where the reflected wave is an inverted image of the incident wave.

Compressional (Longitudinal or P) Wave. Normal sound is transmitted by material alternately compressing and expanding. This type of wave propagates at the compressional wave speed, C_{ℓ}, which is a function of the material's bulk modulus, density, and shear rigidity:

$$C_\ell = \left(\frac{K + \frac{4G}{3}}{\rho} \right)^{1/2} \qquad (1)$$

where K = bulk modulus

G = shear modulus

ρ = material density

Particle movement is along the axis of wave propagation.

Shear (Transverse or S) Wave. When a solid is stressed transversely (sheared) by an oscillating driving force, a different type of wave is generated that propagates at the shear wavespeed, C_t. This speed is a function of the shear modulus or rigidity and density.

$$C_t = \left(\frac{G}{\rho} \right)^{1/2} \qquad (2)$$

Particle motion is perpendicular to wave propagation direction.

Attenuation. Both compressional and shear waves are reduced in amplitude as they propagate through a medium. Part of this loss is a result of spherical spreading. This occurs because sound is generally generated at a point and as it spreads out the acoustic energy must progressively fill a larger volume. The amplitude is reduced. Absorption occurs as acoustic energy degrades to thermal energy through friction or other means. Shear and compressional wave absorption coefficients, α_ℓ and α_t, respectively, can be assigned to sediments. Both are functions of the physical properties of the sediment.

Acoustic Impedance. The acoustic impedance is defined rigorously as the proportionality factor between pressure and velocity in a propagating acoustic wave. In simple theory, the acoustic impedance is ρC_ℓ.

Scattering. When an acoustic wave is reflected from a "rough" surface the returning energy is scattered in different directions. The apparent net reflectivity is less than it would have been for a "smooth" surface. "Rough" and "smooth" are relative terms that depend on the height of the irregularities relative to the acoustic wave length.

Focusing. Sound reflecting from a concave upward surface is concentrated at particular points. When the ship passes these points the apparent reflectivity of the bottom may exceed 1.0.

Frequency Dependence. Many acoustic phenomena are essentially independent of sound frequency (e.g., sound speeds, reflection from a nonattenuating medium), but two items that have a strong frequency dependence are attenuation and scattering. The attenuation coefficient appears to vary almost linearly with frequency (Hamilton, 1972), although this subject is being debated in the literature (Stoll, 1977). Scattering has a more complex relationship to frequency (or wavelength, as discussed above).

Interference. When sound pulses are reflected from a layered material, returning pulses may interfere with incident pulses. Interference may be constructive or destructive, depending on the layer thickness relative to the wavelength.

Theory

Liquid-Liquid Reflection. The simplest and most commonly applied theory has to do with normal reflection of sound from a liquid-liquid interface. The applicable relation is termed the Rayleigh Formula:

$$R = \frac{\rho C_\ell - \rho_o C_o}{\rho C_\ell + \rho_o C_o} \tag{3}$$

where subscript o and no subscript refer to the upper and lower liquids, respectively.

For oblique reflection the Rayleigh Formula is (after Urick, 1967, p. 127):

$$R = \frac{\rho C_\ell \cos\theta - \rho_o C_o \cos\beta_\ell}{\rho C_\ell \cos\theta + \rho_o C_o \cos\beta_\ell} \tag{4}$$

where θ = angle of incidence (relative to a normal to the interface)

β_ℓ = angle of refraction

β_ℓ and θ are related through Snell's law.

Sediments behave acoustically enough like liquids that these simple equations have application. They have formed the basis for several field investigations.

Liquid-Solid Reflections (no absorption). For oblique reflection from a solid that can conduct shear waves (but does not absorb acoustic energy), the reflectivity is (Merkulova, 1970):

$$R = \frac{\dfrac{\rho C_\ell \cos^2 2\beta_t}{\cos\beta_\ell} + \dfrac{\rho C_t \sin^2 2\beta_t}{\cos\beta_t} - \dfrac{\rho_o C_o}{\cos\theta}}{\dfrac{\rho C_\ell \cos^2 2\beta_t}{\cos\beta_\ell} + \dfrac{\rho C_t \sin^2 2\beta_t}{\cos\beta_t} + \dfrac{\rho_o C_o}{\cos\theta}} \tag{5}$$

where β_ℓ and β_t are the compressional and shear refraction angles, respectively (related to θ through Snell's law).

Liquid-Solid Reflection With Absorption. The relations for reflectivity and phase shift for the general case of relfection from a plane surface are given by Merkulova (1970). The impedances and angles of refraction are written as complex variables that include the absorption coefficients. These relationships are lengthy and will not be included here. However, they have been computer programmed and will be used in a later section to assess the sensitivity of reflectivity to changes in the acoustic parameters.

Discussion of Basic Relations. Equation 5 reduces to Equation 3 for normal incidence. This indicates that it is impossible to determine anything about shear wave behavior (i.e., discriminate between liquids and solids) from normal reflectivity. It also indicates that since normal reflectivity is so simply modeled it may be more usable in the real world where many complicating factors make data analysis difficult.

Looking at Equation 3, the basic relationship for normal reflectivity, it is seen that a measurement of R (and a knowledge of C_o and ρ_o for water)yields only the product ρC_ℓ. There is no direct way to separate density and sound speed through a normal reflectivity measurement. However, since most surficial sediments have about the same sound speed, this is not too significant a problem. Also, simple oblique techniques exist for measuring sound speed (Dix, 1955; Bryan, 1974), which can be used to isolate density (Porter & Bell, 1974). Whether sound speed is assumed or measured, the final output of normal reflectivity measurement is sediment density.

Equation 5 and the full liquid-solid reflection with absorption relationships contain all the acoustic parameters. If the seafloor were as ideal as the conditions assumed in formulating the equations, reflectivity and phase shift could be measured as a function of incidence angle and all the parameters obtained. The most important of these to geotechnical engineering is probably the shear modulus, G, obtained directly from C_t through Equation 2. This parameter relates to the resistance to shear developed between particles at low strain. It correlates strongly with the undrained shear strength, which is the resistance to shear at large strain and is of paramount importance in anchor and foundation design. Incidentally, the compressional wavespeed, C_ℓ, also depends slightly on G (Equation 1). However, G is so overshadowed by K in Equation 1 that it would be virtually impossible to estimate G with any degree of accuracy.

The possibility of measuring shear wave velocity and, consequently, G and shear strength, s_u, directly through oblique reflectivity measurements will be considered in a later section.

PREVIOUS FIELD WORK

Although seismic reflection techniques have been used at sea since the early thirties, the use of small, nonexplosive sound sources fired at precisely spaced intervals and recorded on a precision variable density recorder began in the middle

1950's (Knott and Hersey, 1956). The technique was called Continuous Seismic Reflection Profiling to distinguish it from typical oil exploration geophysical methods used on land, and later, at sea. Other terms used include subbottom profiling, geological echo profiling, and continuous acoustic subbottom profiling. Seismic Reflection Profiling (SRP) is probably the most common term presently in use.

Early use of SRP followed the techniques of geophysical exploration; that is, the determination of simple stratigraphy and geological structure. These data result from the closely spaced firing of a sound source, receiving the echo events from the seafloor and subseafloor strata, bedrock, fault plains, etc., and presenting them in analog form (usually with a high vertical exaggeration).

This method, in effect, measured and plotted the sonar range from the survey ship to various reflectors. Later, workers began to examine the echo itself for clues as to what kind of a surface reflected it. These early attempts at reflection analyses were subjective or qualitative. Attempts have also been made to quantify the acoustic reflection data for more thorough and objective analyses. These three methods of interpreting the acoustic response of submarine soils - geologic mapping, qualitative analysis, and quantitative analysis - will now be reviewed briefly.

Geologic Mapping

Most of the marine geology and geophysical literature is included under this application of SRP. The work of Curray and Moore (1963) represents an ambitious but realistic attempt to distinguish facies changes under conditions of marine transgressions.

Qualitative Analysis

Damuth (1975) reported that the Western Equatorial Atlantic could be categorized into 10 seafloor provinces based on qualitative analyses of subbottom reflection profiles. Short pulse length (<5 ms) 3.5 and 12 kHz sound sources were used. Many different aspects of the echo events were considered, such as pulse length, whether or not hyperboli were recorded and their types, the existence of subbottom strata, whether they were continuous or discontinuous, topography, etc. Cores were taken in the study area and some correlations were established. Seafloor areas with numerous coarse-grained strata within the length of the core could be distinguished from areas with a fine-grained sediment profile. Similar results were reported by Akal (1974). Damuth's (1975) work was largely geological mapping by subbottom profiler interpretation with sufficient data (tracklines) to group the results by areas displaying common characteristics (such as numerous hyperboli that are always tangent to the seafloor). If a single subbottom profile had been made across the study areas, some of these aberrations of the record would probably have gone unnoticed.

King (1965) was able to distinguish four types of bottom in a survey near Nova Scotia using an echo sounder of 14.25 kHz and a 1-ms pulse length. The classification was based on the bathymetry, as well as the relative degree of compaction of the bottom sediment as suggested by the depth to which the sound penetrated the bottom. Collected in the study area and analyzed for grain size distribution were 141 bottom samples.

A joint study of Coos Bay, Ore., by the Army Corps of Engineers and Oregon State University (1976) attempted to classify bottom sediment types by side-scan sonar. The textural quality of the recording was used as well as bed forms. The side-scan sonar provides the parameter of bed form identification not available from either depth sounder or subbottom profiling acoustics. Combination subbottom profiles and side-scan sonar units are presently available to provide data on the detailed shape of the bottom, as well as the geometry (structure) of the subbottom, plus the various qualitative indications that appear on the sonargraphs (the limit of whose interpretation is bounded only by the imagination and ingenuity of the interpreter).

Quantitative Analysis

Danbom (1976) reported the results of an acoustic reflection study in Block Island Sound, south of Connecticut and Rhode Island. An area that had been previously mapped by systematic bottom sampling was traversed several times using a 3.5 kHz acoustic signal. Although the initial signal was not monitored for intensity, the amplitudes of echo events were measured. The return echoes were, therefore, assigned a number value and the area was contoured. Nearly 300,000 individual measurements of reflection amplitude were obtained along 182 nautical miles of trackline. These were grouped into 1,205 data points and contoured. Analyzed for mean grain size for comparison with the reflection amplitude data were 84 bottom sediment samples from two different surveys.

Efforts to correlate mean grain size with reflection amplitude met with difficulties because the amplitudes suggested a range larger than that indicated by sampling. Errors in positioning between two sampling surveys and the acoustic survey could have contributed to the problem. Also, the initial amplitudes of the acoustic signals may have varied during the survey (20-hr duration). When the initial signal and the echo amplitudes are measured and compared, the resulting reflectivity coefficient is independent of instrument variations and so is a more reliable parameter with which to work.

Akal (1972, 1974) reported efforts to measure bottom reflection loss variation in the Mediterranean with respect to frequency and angle of incidence, alteration of the reflected waves, and scattering. The relationship of these measurements to the physical properties of the sediments was also investigated.

An early and definitive attempt to classify bottom sediments acoustically was made by Breslau (1965), who measured acoustic reflectivity at many locations in the North Atlantic Ocean. Results were compared with the physical properties of core samples. Breslau's results are best summarized in Figures 2 and 3. Figure 2 shows that a bottom loss of 12 db could be interpreted anywhere from 38% to 72% porosity. Only in the extremes of sediment type (namely, sand and clay) are the bottom loss data unambiguous. Over an 18-db loss, the porosity varies only from 60% to 72%, while below a 10-db loss, the range extends from 28% to 61% porosity.

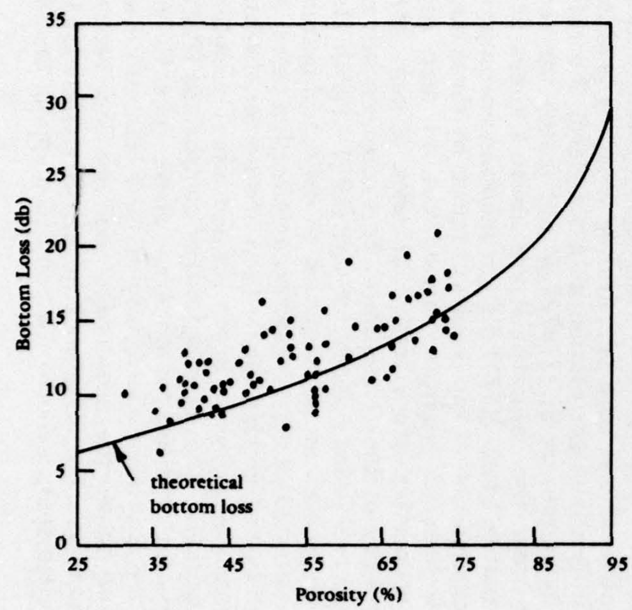

Figure 2. Bottom loss measurements at sediment stations versus measured porosity of the sediments. (From Breslau, 1965, Figure 6)

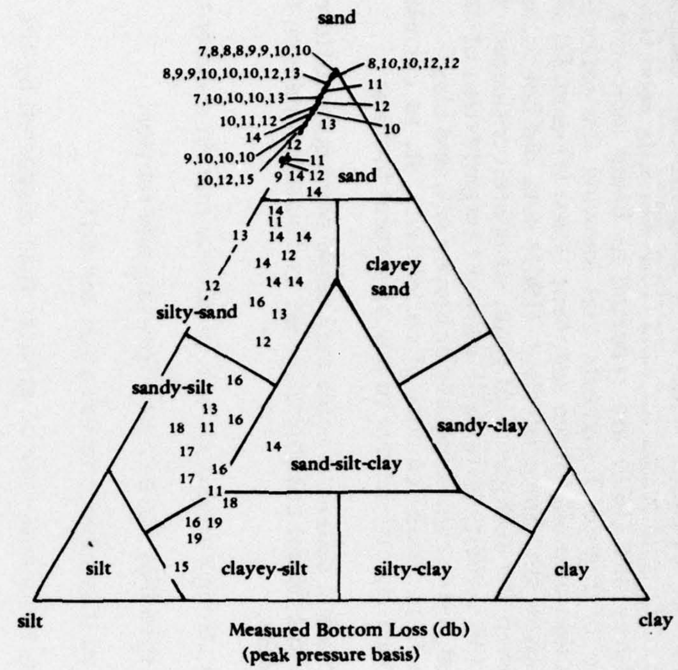

Figure 3. Bottom loss measurements at sediment stations plotted on a sand-silt-clay diagram. (From Breslau, 1965, Figure 8)

Figure 3 shows the plot of Breslau's data on a sand-silt-clay diagram. Although the average values of bottom losses for sand (10.9 db), silty sand (13.8), sandy silt (15.4 db), and clayey silt (16.0) are reported as being indicative of sediment type, consideration of Figure 3 suggests that knowing the reflection coefficient allows categorization into only three sediment types: (1) sand, (2) silty sand, and (3) sandy silt or clayey silt. Since Breslau's (1965) data did not include clay, we may assume that when the full gamut of grain sizes are considered, the reflection coefficient alone (no velocity data) will allow a categorization of data into four sediment types: sand, silty sand, sandy silt or clayey silt, and clay.

The failure of Breslau's field measurements of reflectivity, R, to correlate more closely with values of porosity may be due to any of several factors:

1. Acoustic measurements and sediment cores may come from quite different locations due to positional imprecision, possibly as great as 1 nautical mile on the shelf where LORAN A was used.

2. Porosity may not be a strong correlation to R in natural marine sediments.

3. Bathymetric irregularities may have caused focusing and scatter.

4. The instrumentation itself is subject to variation and drift.

5. The real variability in sediments may be greater than suggested by the 77 samples.

Barnes et al. (1972) reported an attempt to verify Breslau's work in acoustic reflectivity field mapping using 2.5 kHz and 41 kHz sources in San Francisco Bay. The bottom samples collected were positioned by Hastings Raydist. Sixteen core sites were established (with at least one core per site) on a survey grid totalling about 26 nautical miles. With Breslau's correlation as a standard, the reflection coefficient values reported by Barnes et al. (1972) do not match the sediment types sampled in the survey area. The values of R are about 4 times what the sediments suggest. Although Barnes et al. (1971) did not mention entrapped gas in the cores taken, it offers an explanation of the results obtained by these authors.

By far the most comprehensive program carried out to map sediment engineering and geological properties acoustically has been a joint effort of Raytheon, Inc. and the University of New Hampshire. This research was pursued under grants from the National Sea Grant Agency for 4 yr (1970 - 1974). The work culminated in implementing techniques at sea designed to collect simultaneously and remotely estimates of compressional wave velocity, attenuation rates, and the reflection coefficient as a function of incident angle (Bell and Porter, 1974).

Reports of detailed comparisons between acoustics and direct sampling have not been published by these workers. The most definitive comparison (Porter and Bell, 1975) involved the acoustic profiling of an area where recently dumped dredge spoil was mapped by the Raytheon-University of New Hampshire system. The conventional analog record shows the pre-dredge spoil seafloor beneath the more highly reflective spoil material. The difference in reflectivity coefficients is sufficient to delineate the dredge spoil, even to the point of mapping the edges of the spoil where it is either too thin or too discontinuous to be mapped by continuous subbottom profiling alone. No attempt to rigorously compare direct sampling with acoustics is made.

An added advantage of measuring compressional wave velocity underway was brought out when the high reflectivity of the dredge spoil suggested the possibility of entrapped gas. However, since sound velocities were high in the dredge spoil the possibility of gassy sediments was eliminated.

Porter (1976) describes an experiment where the Raytheon-University of New Hampshire system attempted to classify sediments acoustically in areas of unstable sediment in the Mississippi Delta region. Gassy sediment could be located and identified as such, but the three parameters measured (R, C, and A) were so strongly affected by gas content that their interpretation became impossible. Porter (1976) provides no comparison between cores and acoustics, but the purpose of the survey was to attempt to correlate areas of instability with having entrapped gas in the sediment.

Although Porter et al. (1974) report extensive physical sampling in support of their acoustic studies, the details of core location relative to acoustic tracklines and correlation factors are not presented. However, Raytheon (1975) does report that it has commonly encountered only a 1% scatter on velocity measurements and about 10% scatter in calculated sediment densities at the juncture of intersecting tracklines or during repetitive traverses across the same test sites. These workers (Raytheon, 1975) also point out that measurements of density and velocity in control cores along acoustic tracklines show far greater scatter than the acoustically determined values.

Caulfield et al. (1976) also reported results of reflectivity measurements. Signals of 12, 7, and 3.5 kHz were used in attempts to measure soil characteristics through an ice layer in the Mackenzie Delta near Tukloyaktuk, Northwest Territory, Canada. Four sites were occupied. Interpreted acoustic impedances were related iteratively to grain size and porosity of sediments to depths 25 m below the seafloor. The Caulfield et al. (1976) experiment did not provide a basis for assessing the accuracy of quantitative acoustic measurements. Results of tests on core samples were used to calibrate the acoustic measurements. Therefore, good agreement automatically occurred between the two.

Tyce (1976) found wide variation (>10 db) in subsurface reflectivity results, using a deep-towed, near-bottom, 4-kHz subbottom profiling system. The causes of such fine scale variations have not been determined, but the data are significant to anyone attempting to map the geotechnical properties of the seafloor by use of reflection coefficient. Measurements of attenuation, compressional sound velocity, and shear strength suggested to Tyce (1976) that the high subsurface reflection coefficients may be caused by early lithification.

PRESENT GEOTECHNICAL APPLICATION

In the known field acoustic studies, the only parameters quantified were relative reflectivity, reflection coefficient, and compressional wave velocity. From these measurements, density can be directly calculated, and porosity can be indirectly determined. From these parameters a rough grain size classification was obtained) e.g., sand, silt, or clay).

Shear strength, which is usually the most important parameter to geotechnical engineers, was not included in the discussions. The question then arises: can existing acoustic technology provide any useful information to geotechnologists? The answer is a tentative yes, particularly for direct-embedment anchors. Figure 4 (from Taylor, 1976) summarizes the results of pullout tests with the CEL 20-kip anchor through about mid-1974. It shows that the parameter, η (holding capacity/anchor kinetic energy), is closely related to a rough sediment classification (silty sand, stiff clay, or soft clay). At worst, it appears that the holding capacity parameter varies by only $\pm$50% if the classification is known. If the classification is not known, the parameter can vary between 2 and 11. From the work of Breslau (1967), Barnes et al. (1971), and Raytheon-University of New Hampshire (1975), it appears that it is possible to discriminate at least between sand and clay, using normal acoustic reflectivity. Determining whether the clay is "stiff" or "soft" may or may not be possible. The difference in density between the two is not very large, but if a general area is known relatively well (i.e., a few cores have been taken) it might be possible to pick out stiff and soft spots from the acoustic records. This technology would need to be developed.

Actually, knowing whether a clay is stiff or soft is not as important as it might seem. Recent work in predicting long-term holding capacity* (data plotted in Figure 4 is short term) has shown that the capacity of anchors in stiff, overconsolidated clays degrades with time. Whether it degrades all the way to the value for soft clay in the long term is not known, but at least the holding capacities for stiff and soft clays become closer with time.

Not included in Figure 4 but also of considerable importance in embedment anchor design is the influence of exposed or thinly covered seafloor rock. If a bottom is rocky, the type of anchor used and the sorts of holding capacities attainable are very different from those in sediments (Wadsworth, 1976). Normal acoustic reflectivity provides a good means of locating rocky seafloors.

With other types of anchors and foundations, a simple knowledge of rough bottom classification may not be as valuable. The reason it works so well with embedment anchors is because of their two phases of operation: penetration and pullout. If the bottom is soft, greater penetration is achieved, which leads to higher holding capacities than would at first be expected. Stiff bottoms yield low penetrations and correspondingly lower holding capacities than at first expected. Much of the influence of sediment properties is cancelled out. With many types of foundations and anchors, this is not the case. They are placed in a particular position (i.e., footing on the surface, cable burial to a predetermined depth) that does not vary with the sediment type. When the devices are put into service, they must cope with the conditions present - not those that in some way are determined by the method of installation. Knowledge of a sandy bottom would still be valuable since these are generally known to provide a "good" foundation for small structures. If the bottom is clay, it would probably be necessary, in addition, to know the shear strength as well. This is not possible at present with normal reflectivity acoustics. Procedures for estimating shear strength variations from normal reflectivity acoustics in a well-controlled, lightly cored area may be possible but require development.

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*For further information, contact R. Beard, CEL.

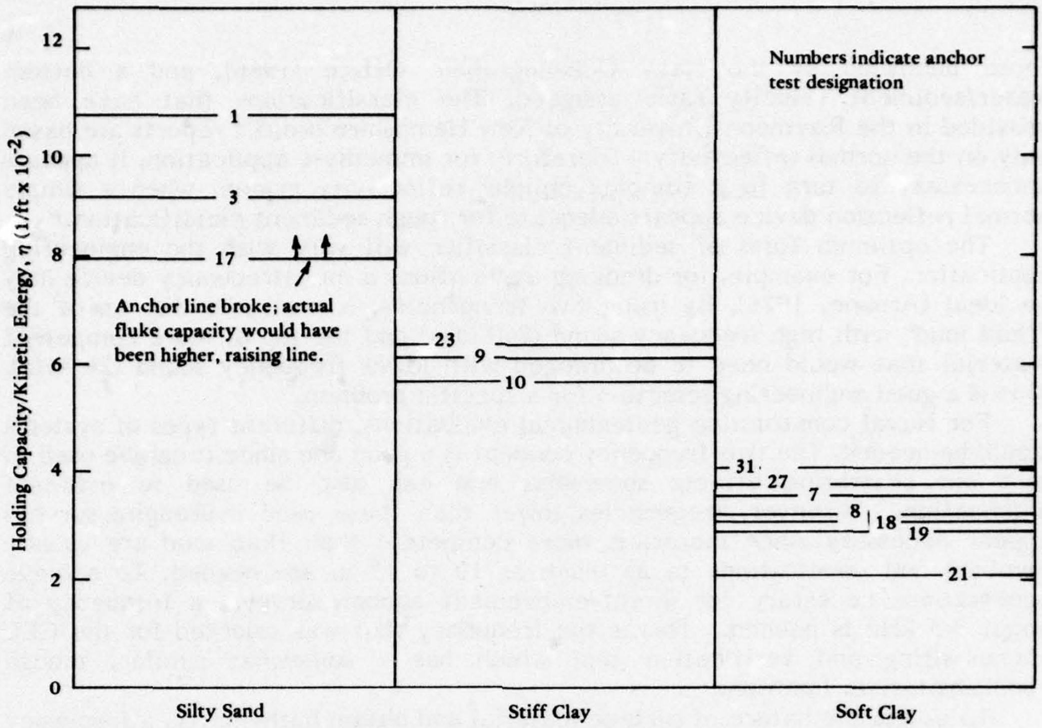

Figure 4. Relationship between the parameter (holding capacity/kinetic energy) and soil type for CEL 20K direct embedment anchor.

PRESENT USE RECOMMENDATIONS

As discussed in the preceding section, knowledge of a rough sediment classification can be quite valuable in certain specific applications of marine geotechnology. This knowledge appears to be obtainable with several acoustic systems that have been used: Breslau (1967); Barnes et al. (1972); Bell and Porter (1974); Arnone (1976). All but the system described by Bell and Porter (1974) used purely normal reflectivity acoustics. In the present state-of-the-art, therefore, the bottom (sand, clay, or rock) can be roughly classified using normal acoustic reflections. Two, or perhaps more, layers can be handled, but accuracy probably deteriorates rapidly with increasing subbottom depth.

The Raytheon-University of New Hampshire system, designed to have broader application, utilizes oblique as well as normal reflectivity and has been used to measure compressional wave velocity rather accurately(+1%).This system appears to offer little more than the much simpler normal reflectivity systems. Its major unique capability is the measurement of compressional wave velocity, which is usually not a particularly valuable parameter, since it could probably be estimated from the reflectivity or inferred density, or by a technique suggested by Hamilton (1969) where bottom water velocity is obtained from tables such as those published by the Navy Oceanographic Office (1966), and a bottom water/sediment velocity ratio assigned. The classifications that have been provided in the Raytheon-University of New Hampshire project reports are based only on the normal reflectivity. Therefore, for immediate application, it appears unnecessary to turn to a complex oblique reflectivity system when a simple normal reflection device appears adequate for rough sediment classification.*

The optimum form of sediment classifier will vary with the engineering application. For example, for dredging applications a multifrequency device may be ideal (Arnone, 1976). By using two frequencies, it measures the top of the "fluid mud" with high frequency sound (240 kHz) and the top of more competent material that would need to be dredged with lower frequency sound (24 kHz). This is a good engineering selection for a specific problem.

For Naval construction geotechnical evaluations, different types of systems would be needed. The two-frequency concept is a good one since it can be used to sort out scattering effects somewhat and can also be used to estimate attenuation. However, frequencies lower than those used in dredging surveys appear necessary since materials more competent than fluid mud are usually involved and penetrations to as much as 10 to 15 m are needed. To achieve penetrations necessary for direct-embedment anchor surveys, a frequency of about 3.5 kHz is needed. This is the frequency that was selected for the CEL anchor-siting and verification tool which has a somewhat similar, though nonquantitative, function.

To assess the nature of surface material and obtain bathymetry, a frequency of about 12 kHz should be used. Therefore, a normal reflectivity system that uses 3.5 and 12 kHz and that measures amplitude of outgoing and incoming signals would satisfy most Navy subbottom depth requirements. The results would be analyzed using a liquid-liquid model (Equation 3) to obtain sediment acoustic impedance, to estimate density, and to infer classification. This is a state-of-the-art application and is relatively simple.

POTENTIAL GEOTECHNICAL APPLICATIONS

Shear Wave Velocity Measurements

It was suggested earlier in the discussion of theoretical relationships that since the shear wave velocity of the seafloor enters into the acoustic reflection equations, it should be possible to measure shear wave velocity using oblique reflectivity measurements. Shear wave velocity, in turn, relates well to the undrained shear strength, the prime geotechnical parameter. The Raytheon-University of New Hampshire system has potential for measuring shear wave velocity (Bell and Porter, 1974), but thus far has not been applied to this task. Given this apparent availability of developed theory and working equipment, the authors proceeded to a sensitivity analysis to evaluate the possibility of

*One area where measurements of compressional velocity might be valuable is in cases of gas-loaded sediments, as discussed previously.

measuring almost directly the shear strength of sediments using acoustics as follows:

1. The general acoustic reflection model of Merkulova (1970) was programmed to yield $|R|$ as a function of incidence angle, θ. The parameters of the model are C_o, C_ℓ, C_t, ρ_o, ρ, α_ℓ, α_t.

2. The parameters, C_ℓ, α_ℓ, and α_t, were set up as direct functions of sediment density, ρ, using the work of Hamilton (1974) (α_t also requires C_t, calculated below).

3. The parameters C_o and ρ_o of water were taken as 1.50 km/s and 1.04 Mg/m^3, respectively.

4. The shear wave velocity, C_t, was expressed as a function of undrained shear strength, s_u, for clays and relative density, D_r, for sands. To obtain this function, data from Seed and Idriss (1970) relating the shear modulus, G, at very low strain levels (10^{-4}) to s_u and D_r were used. These data show $G = 2{,}000\ s_u$ for clays and $G = 1{,}000\ (16 + 0.6\ D_r)\ (\bar{\sigma}_m)^{1/2}$ psf for sands. The term $\bar{\sigma}_m$ is the average effective stress or about $0.6\rho_b Z$ with ρ_b as the sediment submerged unit weight and Z as the subbottom depth.

5. The net result of steps 2 through 4 was to express the acoustic parameters in terms of the engineering parameters, ρ, s_u, and D_r. It was then possible to select values of these engineering properties and obtain reflectivity versus θ.

CEL has investigated many sites in the Atlantic and Pacific Oceans. Typical values of engineering properties for each of these sites were selected and inserted into the model. The properties of the selected sites are given in Table 1, and the resulting reflectivity curves are shown in Figures 5, 6, and 7. Since sediment properties usually vary considerably with subbottom depth, it was necessary to assume average values over the upper 5 to 10 m. The resulting data are somewhat hypothetical but provide an indication of how properties vary over the world's oceans. The fact that sediment property varies with depth and may influence reflectivity was not considered in this analysis.

As may be seen from Figures 5, 6, and 7, each sediment produces a reflectivity curve that has about the same shape as those of other sediments but differs significantly quantitatively. The typical shape is an almost horizontal line for small θ, followed by a rapid steepening, becoming a nearly vertical line for θ of 45 to 75 deg. The last portion of the curve is nearly horizontal with almost perfect reflection. The θ at which the reflectivity curve is nearly vertical should be quite recognizable in the field and is a good diagnosis of the sediment type. Likewise, the zone of rapidly increasing R with θ produces greater separation of the curves and allows a more accurate classification through reflectivity than does a purely normal measurement ($\theta = 0$). Oblique reflectivity does produce additional information and probably leads to better sediment classification than simple normal reflectivity.

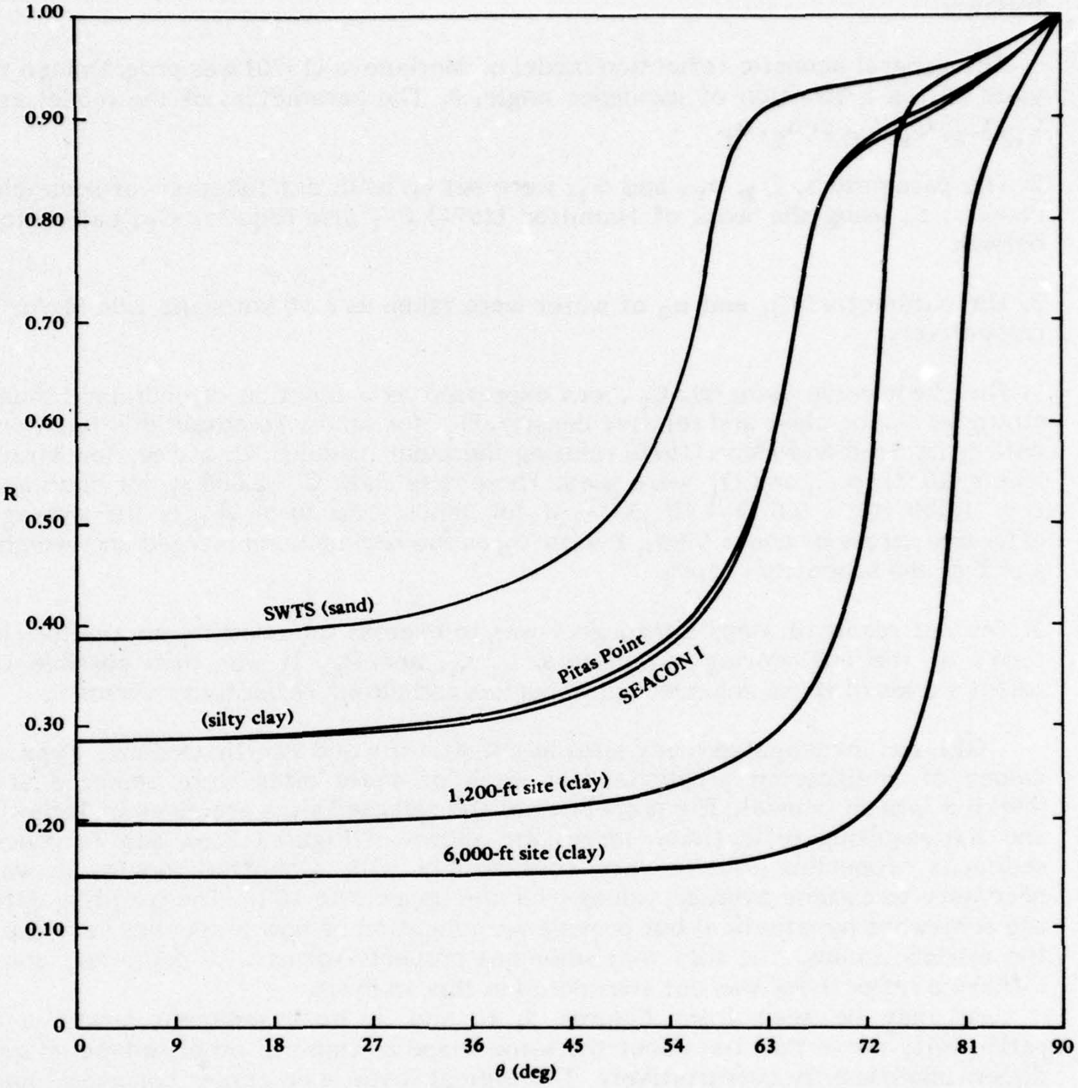

Figure 5. Theoretical oblique reflectivity curves - sites near Port Hueneme, Calif.

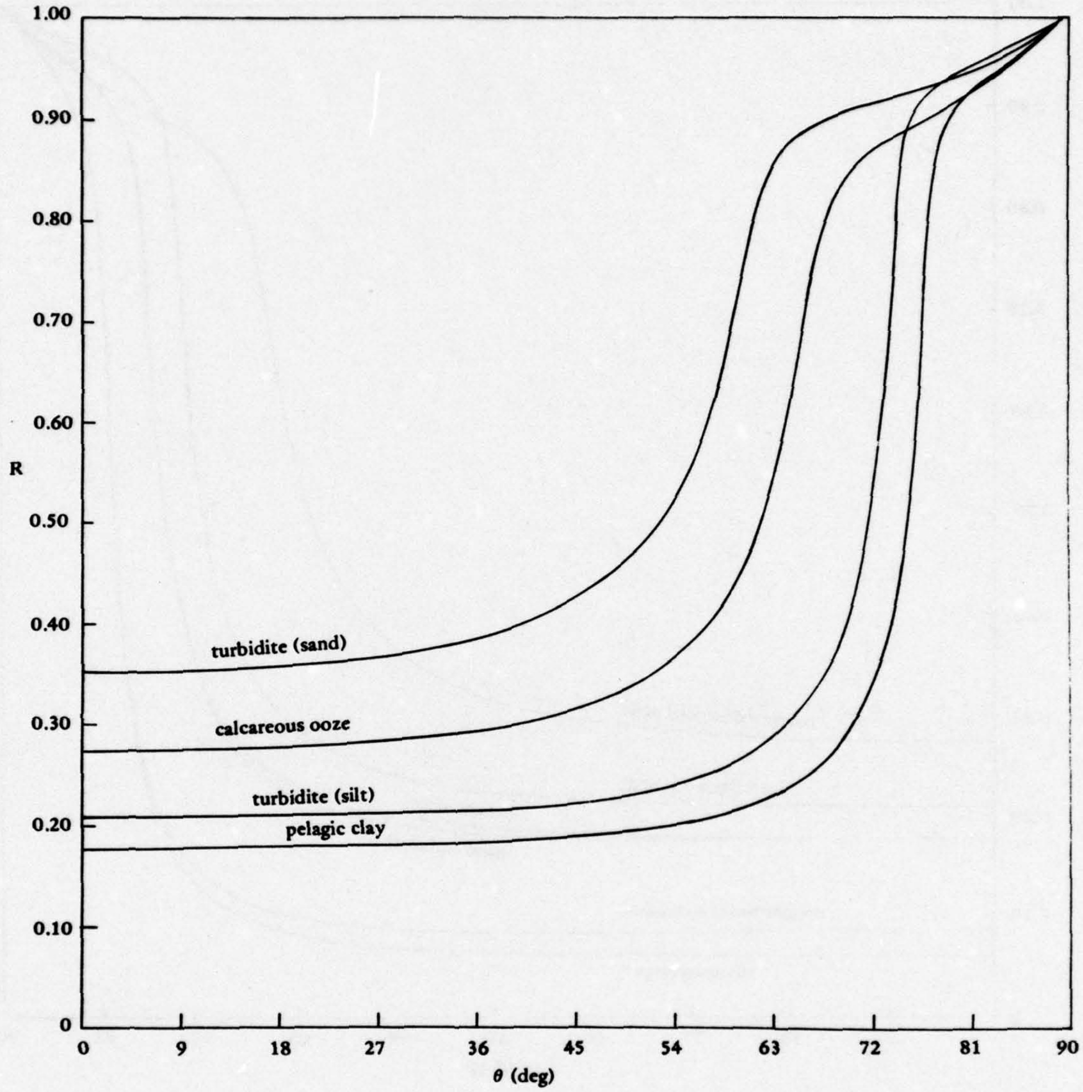

Figure 6. Theoretical reflectivity curves - Atlantic Ocean sediments.

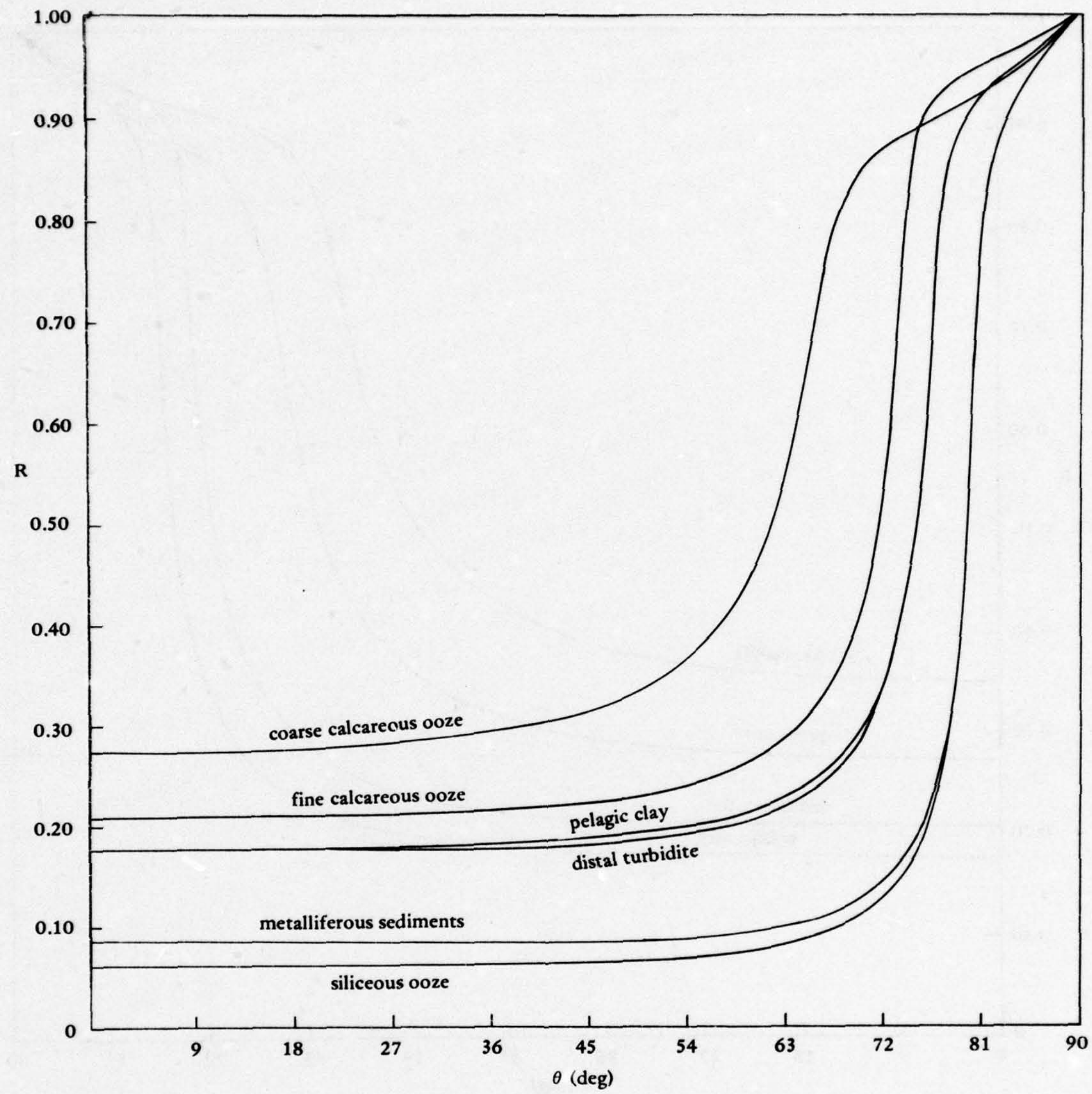

Figure 7. Theoretical reflectivity curves - deep Pacific Ocean sediments.

Table 1. Properties of Selected Sites

Figure No.	Site Characteristics	ρ Mg/m^3	C_ℓ m/s	C_t m/s	α_ℓ db/m	α_t db/m
5	1,200-ft site (clay)	1.51	1560	195	0.098	16
	SEACON I (silty clay)	1.71	1640	152	0.438	48
	6,000-ft site (clay)	1.39	1520	99	0.075	11.5
	Pitas Point (silty clay)	1.71	1640	88	0.438	80
	Shallow water test site (SWTS) (sand)	2.00	1760	162	0.486	17.6
6	Pelagic clay	1.45	1540	68	0.082	19
	Calcareous ooze	1.53	1560	135	0.098	11.3
	Turbidite (sand)	1.89	1720	144	0.548	21.8
	Turbidite (silt)	1.67	1640	153	0.438	48
7	Coarse calcareous ooze	1.67	1640	153	0.438	48
	Metalliferous sediments	1.22	1520	151	0.053	5.3
	Pelagic clay	1.45	1540	84	0.087	16
	Distal turbidite	1.45	1540	154	0.087	8.7
	Calcareous ooze	1.53	1560	135	0.098	11.4
	Siliceous ooze	1.16	1520	109	0.052	7.2
8	s_u = 0.5 psi	1.50	1560	52	0.098	79.9
	s_u = 2 psi	1.50	1560	135	0.098	11.3
	s_u = 4 psi	1.50	1560	191	0.098	8
9	D_r = 30%	1.80	1680	123	0.73	33
	D_r = 90%	1,80	1680	177	0.73	23.2

Unfortunately, it does not appear that the shear wave velocity affects the curves enough to make accurate measurements of this parameter possible, as can be clearly seen in Figures 8 and 9. In the first of these figures, the theoretical reflectivity curves for a clay with a density of 1.5 Mg/m^3 and a shear strength that varies from 0.3 to 4 psi (2.1 to 28 kPa) are plotted. This is practically the full range of shear strengths found in typical cohesive marine sediments and implies a shear wave velocity variation of 50 to 200 m/s. Aside from the 4 psi data, the curves are practically indistinguishable. Even the 4 psi curve is probably not unique enough to be resolvable in the field. Figure 9 for a sand at a subbottom depth of 5 m, density of 1.8 Mg/m^3, and relative density ranging from 30% to 90% (C_t of 123 to 177 m/s) shows a similar problem. The curves are too close to be separated with field measurement of reflectivity; thus, it appears that shear strengths cannot be determined by this technique. It may stil be possible to estimate strength given acoustic data because shear strength and density are usually related. However, the approach is indirect and requires "calibration"; that is, a relationship between density and strength for the particular seafloor being evaluated must be known. At least a few cores and some laboratory analyses will probably be necessary to obtain this information.

It appears that the reason acoustics is not a good technique for examining shear behavior in surficial marine sediments is that we are dealing with two materials - water and sediment - that do not transmit shear stresses or transmit them poorly. However, both transmit compressive stresses quite well. The net effect is that compressive stresses and waves overwhelm the shear stresses and waves. The usual difficulties of making measurements at sea make it impossible to discern these secondary effects.

Consideration of techniques that can be used to measure shear wave velocity should not stop. If a technique could be developed, the rewards would be great. Perhaps new findings in areas such as nonlinear acoustics may make such measurements possible.

Property Gradients

It is well known that many seafloors do not consist of a series of homogeneous layers separated by clean interfaces as is assumed in acoustic theories. Instead, the densities and strengths (and corresponding acoustic parameters) at least within each layer, typically increase more or less steadily with subbottom depth. This results from the process of consolidation or densification under increasing overburden.

Current acoustic reflection theories do not handle all aspects of this more complicated situation. Geotechnologists would benefit if information on how the properties vary were obtained. For example, weak normally consolidated sediments typically have a void ratio (inversely related to density) that decreases linearly with the logarithm of overburden pressure (directly related to density and subbottom depth). The void ratio of stronger overconsolidated sediments would tend to be more uniform. Knowledge of how density varies with depth into the seafloor would, therefore, provide geotechnologists with an indication of soil shear strength. This approach is far from foolproof; many deep ocean sediments contain varying amounts of opaline silica or amorphous metal oxides that greatly affect the density, independent of overburden pressure. However, such knowledge does provide another piece of information that, when inserted into the whole puzzle, may yield geotechnical data.

Another reason for looking at property gradients is to facilitate analysis of normal reflectivity measurements. In earlier studies (e.g., Breslau, 1967) attempts were made to empirically relate reflectivity and density. The results were not as good as one might expect. One of the reasons for this lack of correlation may be that the seafloor is not uniform as assumed; the returning signal may contain some elements of a simple liquid-solid reflection coupled with reflections from the rapidly consolidating material of the upper few meters. Interference causing reinforcement or cancellation of signal may result and lead to a reflected signal that does not match that expected from simple theory.

Improved theoretical reflection relationships, in keeping with the realities of the first few meters of seafloor, are needed. These would lead to more accurate determinations of soil classification and produce new parameters (e.g., rate of density change with depth) that could correlate with strength in some cases.

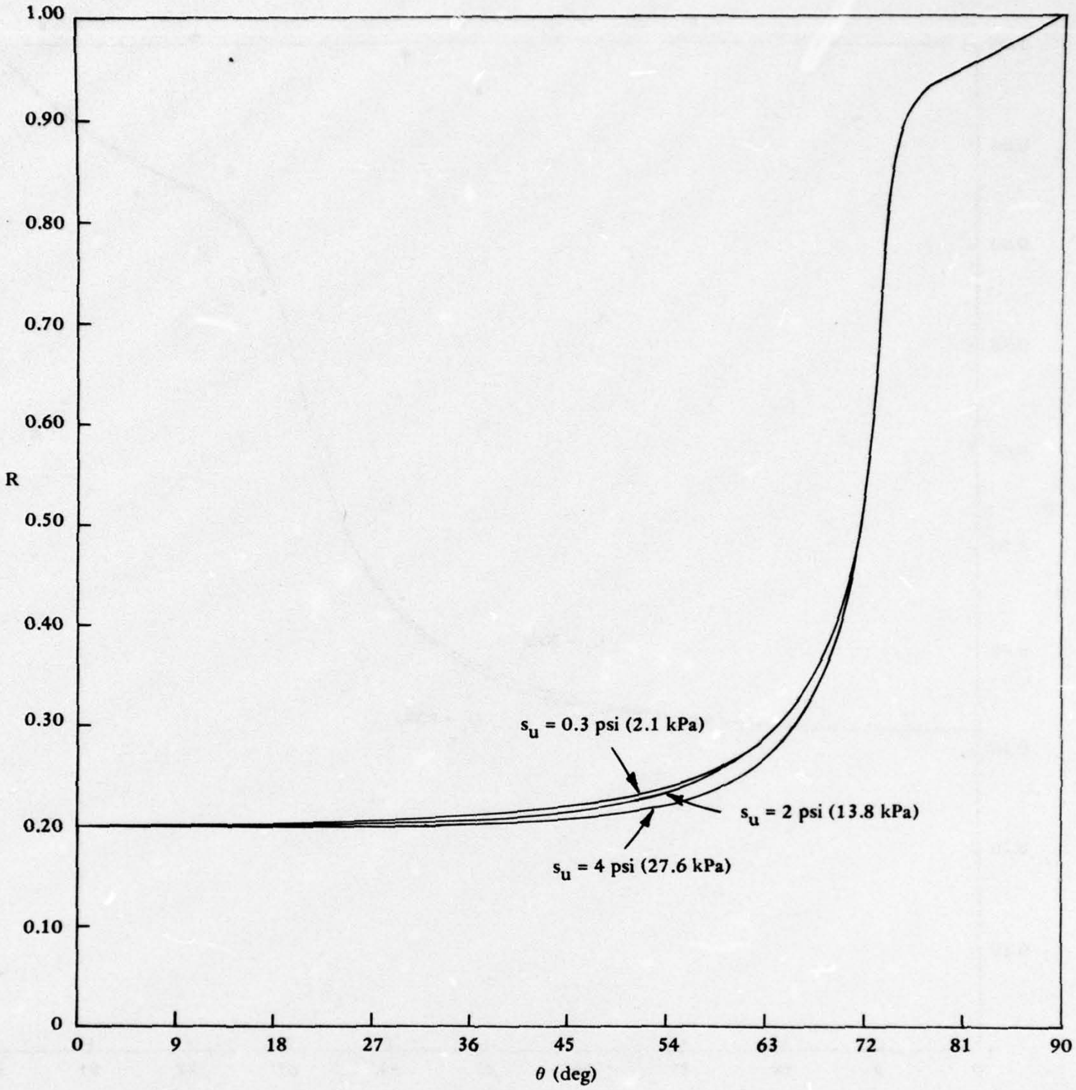

Figure 8. Theoretical reflectivity curve - clay with density of 1.5 Mg/m^3, variable shear strength.

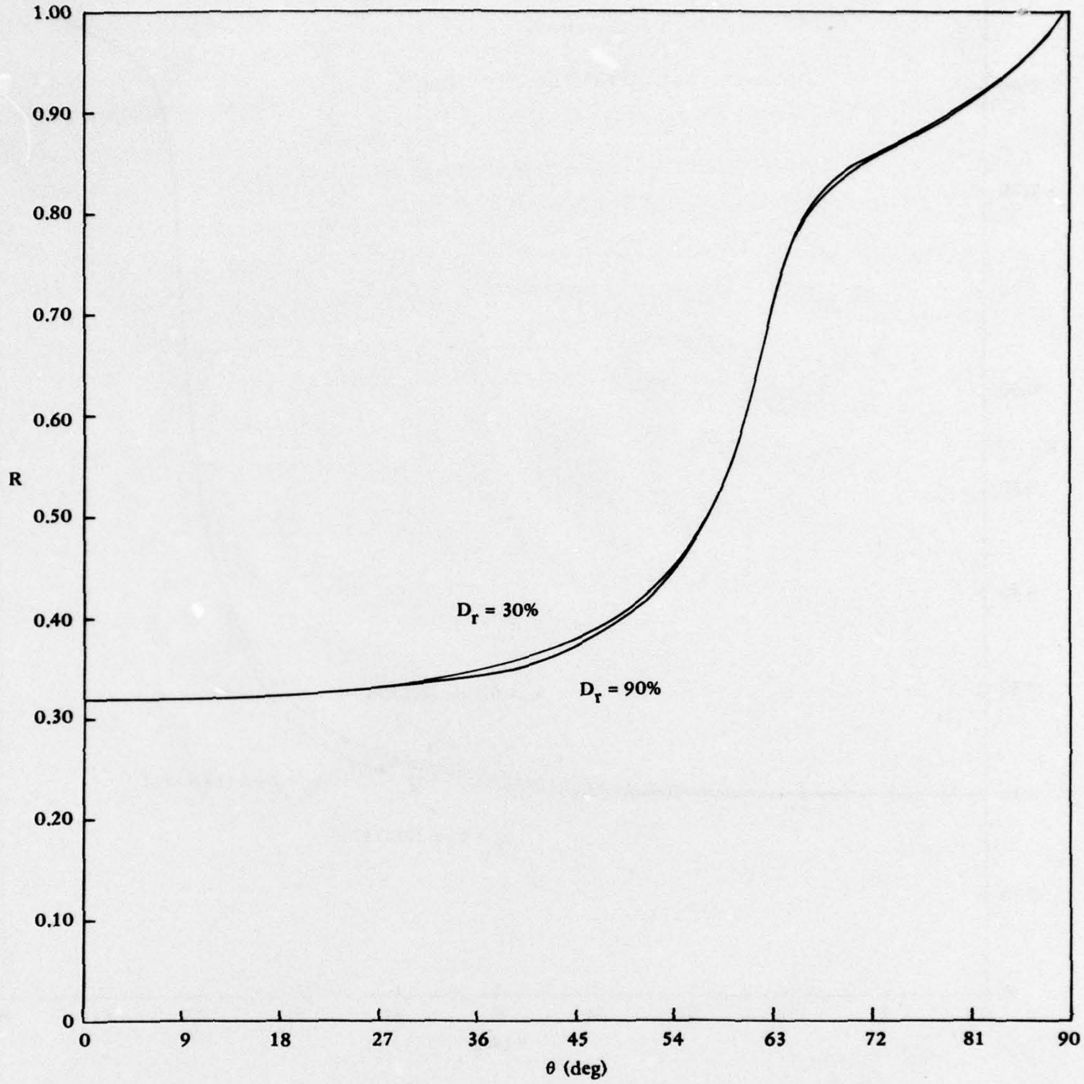

Figure 9. Theoretical reflectivity curves - sand with density of 1.8 Mg/m^3, variable relative density.

Sand Over Clay

In areas of rising sea level, sand and beach deposits often migrate back over clayey marsh areas. This can produce a particularly difficult geotechnical situation. Since the sand is difficult to penetrate with probes or samplers there are no economical ways to mechanically sense the clay. However, if the foundation is large or involves piling, its interaction with the clay may prove disastrous.

Potentially, acoustics can sense clay beneath sand during the site-selection phase. Sites where the clay layer is absent or the sand layer is thick can be selected over less desirable locations. The final selected site would require a test pile or boring to confirm the acoustic assessment.

Even in this situation the use of acoustics is not completely straightforward. Sand is a good attenuator; much energy is lost in passing through the surface layer. Also, the interface between sand and clay is one in which the acoustic impedance of the upper material is greater than that of the lower. This produces a 180-deg phase shift that must be detected to identify the nature of the interface.

Although the technology does not presently exist to classify clays beneath beds of sand, it does appear feasible. Attention needs to be directed toward amplitude, frequency, and incident angle range selection; and procedures need to be developed for recognizing such items as the diagnostic 180-deg phase shift. This technology is particularly needed for amphibious operations where little time for site selection and surveying is available.

FINDINGS

1. Acoustics have been used for many years to study the seafloor qualitatively. Only recently have investigations begun in which the returning signals are used quantitatively to classify the seafloor and measure its properties. Quantitative acoustic measurements can range from those simple systems that measure only the reflection losses of normally incident sound waves to those elaborate towed arrays that measure reflectivity, phase shift, and time delay as a function of oblique incidence angle.

2. Normal acoustic reflectivity has been used by a number of investigators to measure remotely the density of marine sediments. Since density correlates relatively well with grain size for most sediments, these measurements have also been used to classify the sediments. The density measurements appear to be accurate to about $\pm 10\%$. This is strictly an estimate since none of the experiments conducted to date have had rigorous enough control to state the accuracy of acoustically measured density relative to ground truth.

3. Simple oblique reflectivity arrays have been used to measure compressional wavespeed to about $\pm 1\%$.

4. These density and compressional speed accuracies are adequate to separate most sands and clays and may allow division into four or more categories. This

separation may be adequate to estimate the holding capacities of direct embedment anchors and serve as a basis for initial site selection (particularly in the near shore where sands are common).

5. Present accuracies are not adequate for detecting more subtle differences; i.e., strong clay versus soft clay, sand of high relative density versus one of low relative density.

6. Shear wave velocity enters into the oblique reflectivity equations and also correlates well with shear strength. However, the range of shear wave velocity that relates to the range of shear strength common in the ocean does not appear to affect the reflectivity curves by a measurable amount. Shear behavior is masked by mass effects (density).

7. Virtually all acoustic reflectivity work and modeling have included the assumption that the seafloor is composed of homogeneous layers. It is known, however, that surficial marine sediments more commonly display strong gradients of properties rather than clear layer interfaces. The presence of gradients may be one reason why the measurement of density has not been particularly good. Other reasons include focusing, scattering, obtaining samples at locations different from those of the acoustic measurements, sample disturbance, and instrument variability.

8. Oblique reflectivity provides the opportunity to obtain better measurements of density. At relatively large angles of incidence (45 deg or more) the difference between the reflectivities of different density sediments greatly increases. Better resolution can be obtained at such angles.

9. The problem of locating clay beneath a shallow bed of sand is critical in many geotechnical surveys. Acoustics can provide an expedient means of doing so; however, this technology does not presently exist.

RECOMMENDATIONS

The following recommendations are made:

1. Evaluation of the accuracy of seafloor density measurements with a simple oblique reflectivity system: (a) using rigorous navigation control, (b) varied acoustic sampling times at one location, and (c) careful coring at exact locations of acoustic sampling. The acoustics work can be accomplished using two small boats navigating accurately about a marker buoy.

2. Development of the necessary theory and methodology to handle density gradients and the sand-over-clay situation; demonstrate their validity using the evaluation techniques in item 1 at locations of known sediment properties; determine accuracy of measurements.

3. Exploration of the cost of a towed oblique reflectivity system for measuring densities more accurately; estimate the improvement in accuracy that could be achieved (this estimate would be based on the field results of items 1 and 2); decide whether the improvement is worth the cost.

4. Assessment of new developments in acoustics that could be applied to shear wave velocity measurement.

5. Development of promising quantitative acoustic systems for rapidly obtaining geotechnical parameters for Naval applications.

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NAVHOSP LT R. Elsbernd, Puerto Rico
NAVMAG SCE, Guam
NAVNUPWRU MUSE DET Code NPU80 (ENS W. Morrison), Port Hueneme CA
NAVOCEANO Code 1600 Bay St. Louis, MS; Code 3408 (J. Kravitz) Bay St. Louis
NAVOCEANR&DACT Code 450 Bay St. Louis MS
NAVOCEANSYSCEN Code 409 (D. G. Moore), San Diego CA; Code 4473 Bayside Library, San Diego, CA; Code 52 (H. Talkington) San Diego CA; Code 5214 (H. Wheeler), San Diego CA; Code 5224 (R.Jones) San Diego CA; Code 5311(T) (E. Hamilton) San Diego CA; Code 6505 (J. Stachiw), San Diego, CA; Code 6565 (Tech. Lib.), San Diego CA
NAVPETOFF Code 30, Alexandria VA
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NAVSCOLCECOFF C35 Port Hueneme, CA; C44A (R. Chittenden), Port Hueneme CA; CO, Code C44A Port Hueneme, CA
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NAVSEC Code 6034 (Library), Washington DC; Code 715 (J. Quirk) Panama City, FL
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NAVSUPPACT CO, Seattle WA; Code 413, Seattle WA; LTJG McGarrah, Vallejo CA
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NAVWPNCEN Code 2636 (W. Bonner), China Lake CA; PWO (Code 26), China Lake CA; ROICC (Code 702), China Lake CA
NAVWPNSTA ENS G.A. Lowry, Fallbrook CA; PW Office (Code 09C1) Yorktown, VA; PWO, Seal Beach CA
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NSD SCE, Subic Bay, R.P.
NTC Code 54 (ENS P. G. Jackel), Orlando FL
NAVOCEANSYSCEN Hawaii Lab (D. Moore), Hawaii
NUSC Code 131 New London, CT; Code EA123 (R.S. Munn), New London CT; Code S332, B-80 (J. Wilcox); Code TA131 (G. De la Cruz), New London CT
OCEANAV Mangmt Info Div., Arlington VA
OCEANSYSLANT LT A.R. Giancola, Norfolk VA
ONR CDR Harlett, Boston MA; BROFF, CO Boston MA; Code 481, Arlington VA; Code 700F Arlington VA; Dr. A. Laufer, Pasadena CA
PMTC EOD Mobile Unit, Point Mugu, CA; Pat. Counsel, Point Mugu CA
PWC ENS J.E. Surash, Pearl Harbor HI; ACE Office (LTJG St. Germain) Norfolk VA; CO Norfolk, VA; CO, Great Lakes IL; Code 116 (LTJG. A. Eckhart) Great Lakes, IL; Code 120C (Library) San Diego, CA; Code 128, Guam; Code 200, Great Lakes IL; Code 200, Oakland CA; Code 220 Oakland, CA; Code 220.1, Norfolk VA; Code 30C (Boettcher) San Diego, CA; Code 680, San Diego CA; Library, Subic Bay, R.P.; OIC CBU-405, San Diego CA; XO Oakland, CA
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