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OCEAN ENGINEERING SIGNIFICANCE OF MARINE SEISMIC
REFLECTION PROFILING TECHNOLOGY

By

E. F. Pawlowicz

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NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043

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ABSTRACT

Seismic Reflection Profiling (SRP) data of value to the seafloor engineer include: (1) sediment ("soil") thickness, (2) sediment structure, (3) the slope of the bedrock beneath the sediment layer, (4) bedrock topography, if sufficient tracklines are run to permit contouring, (5) bedrock structure, if penetration permits, and (6) acoustical data from which certain physical, engineering, and load bearing properties of an area can be approximated.

Qualitative interpretations of acoustical data are made as a matter of course by the experienced analyzer of SRP records and include such parameters as: (1) echo intensity from the seafloor and subbottom interfaces, indicating hard (high reflectivity) and soft (low reflectivity) layers, (2) penetrability of the seafloor (in unconsolidated sediments) is generally inversely proportional to grain size, (3) point return, or discrete hyperbolic echo returns, indicative of large irregularities compared to the sound frequency recorded, such as boulder beds, or a weathered bedrock surface.

Quantitative interpretations of seismic reflection data include the measurement of compressional wave velocities by underway wide angle reflection techniques. Compressional sound velocities, however, do not vary significantly within saturated marine sediments, so do not give unambiguous solutions to sediment types. Since the shear strength of the sediments is related to the shear wave velocities, its measurement would be of immense value to the seafloor engineer. If the compressional and shear wave velocities are known, the dynamic elastic properties of the material, such as Poisson's ratio, can be calculated. Shear waves, though transmitted by saturated marine sediments, are not propagated through the water column and so are unavailable to surface, or even deep-towed acoustical surveys.

When both the compressional wave velocity and the reflectivity coefficient of a stratum are known, the bulk density can be calculated. The

precise measurement of reflection energies, termed the reflection coefficient, have been attempted with some success, but sediment types cannot consistently be categorized, even broadly as clay, silt, or sand, largely because of the rather widespread phenomenon of surficial sediment-entrapped gas which produces a too-high reflection coefficient for the host sediment.

Three approaches to the problem are indicated: (1) the development of shear wave determination techniques for a rapid measurement of sediment shear strength, (2) a more comprehensive and quantitative analysis of the information of engineering value contained in the bottom-reflected pulse, and (3) the development of a deep-towed, high-resolution subbottom profiler.

Shear wave measurements cannot be made underway, disqualifying this approach for site reconnaissance purposes.

The second approach is being pursued, notably at the Naval Undersea Research and Development Center, San Diego, California and jointly by Raytheon Company-University of New Hampshire.

The third approach has not been vigorously pursued due primarily to the limited number of potential users. The requirement to conduct subbottom profiling over small construction sites in water depths to 6,000 feet is not widespread and so has been bypassed by industry.

It is proposed that a self-powered, deep-towed subbottom profiler be designed and fabricated which will produce high resolution records of at least the first 100 feet of soil in water depths to 6,000 feet.

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INTRODUCTION

The continuous reflection profiling technique (Figure 1) was developed to provide a flexible system to map continuously and accurately subbottom strata in water-covered areas. The sound pulses periodically generated and reflected from the bottom and subbottom acoustic discontinuities are recorded.

The reflected signals are detected by a towed hydrophone array (or transducer), amplified, filtered, and displayed on a precision variable density recorder. Magnetic tape recording and sophisticated digital data processing techniques are sometimes used to optimize the signal-to-noise ratio in the recorded display.

The principal differences between the continuous reflection profiling systems and those systems used for echo-sounding of water depth are the requirements of high acoustic power output and, generally, lower frequency. Although penetrations to 90 feet into the seafloor have been obtained with frequencies as high as 14 kHz (Murray, 1947), lower frequencies are more commonly used. A lower limit to the frequency used is set by the resolution desired--layers thinner than one half the wavelength generally cannot be resolved clearly. Pulse duration is another important factor and must be short for good resolution. In general:

$$2d = v\Delta t \quad (1)$$

where d = distance between reflecting layers (m)

v = velocity of sound in water (1500 m/sec)

Δt = difference between arrival times of the reflected wave fronts

Thus, when the pulse length becomes comparable with the time of $2d/v$ sec, the two layers may not be resolved.

Each type of reflection equipment which differs principally in the type of energy source utilized has its own uses. For a comprehensive discussion of subbottom systems, see Schlank (1968). Briefly, a transducer system operating at frequencies of 1.5 to 12 kHz can show, under favorable circumstances (shallow water, silt and clay sediment), a subbottom structure to depths of 50 m, although penetration of 20 m is more common. A sparker system, operating with high power, will penetrate 1 to

3 km but with less resolution than the transducer system. For penetrations greater than 3 km, explosive source or other high power, low frequency systems are used. The sparker and other like systems may record only a dark line at the water-sediment interface, therefore obscuring any layering in these upper tens of meters of surface sediments. The system selected should be based on the requirements of the survey.

The greatest advantage of seismic reflection profiling over conventional methods is the continuity of the record. The marine construction engineer is supplied with a more accurate and complete understanding of the subbottom geology by these seismic profiles than he could obtain using only borings and depth sounding techniques. Sediment and rock units may be correlated from a few known points, eliminating the need for an extensive boring or coring program.

Borehole data may be correlated with the seismic record. Thus, a survey may proceed from the borehole into unknown areas with an extrapolation of the known strata. Additional borings or cores may be taken in questionable regions or those requiring additional sediment analysis. Sediments, bedrock, and competent strata are mapped simultaneously. For foundation studies, slumping, large- and small-scale faulting and other geologic hazards are located. Differential compaction of overburden, sediment erosion and deposition (scour and fill), eroded channels filled with unconsolidated sediments are among the other geologic features which may be delineated. Continuous seismic reflection profiling provides information from which a detailed and accurate geologic map of a potential construction site could be constructed. Additionally, the records are useful in the planning of dredging, excavation, and other operations requiring knowledge of the "rippability" and trafficability of an area.

In short, continuous reflection profiling can be a most useful tool for the marine construction engineer. Significant subbottom phenomena often overlooked by the use of only conventional depth soundings plus borings are detected.

DATA INTERPRETATION

For a proper geologic and engineering interpretation of the continuous reflection profile, an understanding of the factors which influence the record is necessary. In this report, the interpretation of the data is divided into two categories: the interpretation of the geologic setting (or the qualitative interpretation) and the quantitative interpretation of the acoustic signal.

To interpret accurately the geologic setting of an area from the reflection record, some knowledge of the local and regional geology and the operating characteristics of the system is necessary. Conversely, much information about the physical properties of the sediment can be inferred from the acoustic properties (reflectivity, acoustic velocities, and losses) of the bottom.

The subsequent sections briefly summarize present methods of interpreting a continuous seismic profile record, emphasizing those properties of the acoustic record of value to the marine construction engineer.

DATA INTERPRETATION - QUALITATIVE

The reflected acoustic signal from the seafloor and the subbottom horizons is a function of the reflectivity, or reflection coefficient, of the particular contact, i.e.,

$$\frac{A_r}{A_i} = R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \quad (2)$$

where A_r = amplitude of reflected signal (dynes/cm²)

A_i = amplitude of incident signal (dynes/cm²)

ρ_1 = saturated bulk density of medium 1 (gm/cm³)

ρ_2 = saturated bulk density of medium 2 (gm/cm³)

V_1 = compressional velocity of sound medium 1 (cm/sec)

V_2 = compressional velocity of sound medium 2 (cm/sec)

R = reflection coefficient

Thus, the amplitude of the signal reflected from the bottom and subbottom strata is a function of the bulk density and velocity of sound in the adjacent layers.

The quantity of ρV is termed the acoustic impedance, Z , of the material, i.e.,

$$Z_n = \rho_n V_n \quad (3)$$

Z_1 = acoustic impedance of medium 1 (gm/cm²sec)

Z_2 = acoustic impedance of medium 2 (gm/cm²sec)

therefore

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (4)$$

If the contrast in acoustic impedances of two adjoining layers is great as, for example, in a hard bedrock-sediment contact, a strong reflection is generated. A change in grain size detected in cores, however, may not necessarily cause an acoustic contrast sufficient to be recorded by reflection profiling techniques.

The reflections shown in the record indicate changes in structure, lithology, density, porosity, and other properties which affect the acoustic properties of the sediment or rock. However, a certain amount of geologic reasoning and experience is involved in arriving at a valid analysis of the seismic record.

Some general statements regarding the geologic interpretation of a record will be made, but for a comprehensive treatment of selected areas off the California coast see, for example, Schlank (1968), Moore and Curray (1962), Moore and Palmer (1967), or Moore (1960).

In inferring the rock type of a formation from the seismic record, the internal structure of the subject formation is studied. Such criteria as the roughness of the top surface, the relative reflectivity of the top surface and bedding, and the spacial continuity and degree of disturbance of the bedding are noted (Stride et al., 1969). As an example, off the coast of California (Moore and Palmer, 1967), the reflections from Miocene volcanics are typically strong but show little coherent layering. Dipping late-Tertiary sediments, by contrast, show strong reflections from a series of very continuous bedding planes. Nonlithified Quaternary and recent sediments generally show poor internal stratification.

Occasionally, a sediment-bedrock contact, as between unconsolidated sediments and shale, may show poor acoustic impedance contrast and, therefore, generate a poor reflection. Also, within shale, the acoustic impedance may be nearly constant or gradually changing such that the internal structure is not easily identified.

Although general statements as the above can be made, it is more profitable to study typical annotated seismic reflection records as presented by Schlank (1968) or Hoskins (1964).

Besides information about the rock and sediment type present, the seismic reflection record provides information about the structural setting of an area.

Marine depositional contacts appear smooth and nearly horizontal, while erosional surfaces show irregular and ragged relief and may have angular discontinuities with the underlying rock units. Folded and distorted sediments and rock units are clearly evident, which may indicate the presence of currently active stresses in the region. Slumping is often seen near the base of steep marine slopes.

Of particular engineering importance off the California coast is the presence of small- and large-scale faults. Using the reflection record, the location of the faults can be mapped and the regional or local stress field interpreted (Ridlon, 1969). Additionally, the presence of active faults would enter into the hydrodynamic and safety analysis of an underwater structure (Wilson, 1969).

The thickness of the unconsolidated sediment or overburden can be determined from the acoustic reflection record. Since the speed of sound generally increases with increasing depth of burial, such thicknesses are usually minimal. Since the speed of sound in unconsolidated sediments is approximately that in seawater, the correct magnitude of the sediment thickness is indicated when read directly from the record (Moore, 1960). To calculate accurately the thickness of rock units, however, the acoustic velocity for the rock type present must be known, since this velocity will be considerably higher than that for the water. The relationship between acoustic velocities and properties of sediment and rock will be discussed in detail in a later section.

Thus, reflection records are very effective in the planning of excavation and dredging work and trafficability studies. The amount of material and degree or difficulty in removing it ("rippability") are the kinds of engineering information that can be inferred from the record (Moore and Palmer, 1967; Patterson and Meidav, 1965). Very detailed geologic profiles, useful in many marine engineering applications, can be constructed from the reflection record plus borings or cores for lithologic control.

It must be pointed out that there are problems and limitations with continuous reflection profiling. Since the acoustic signal is propagated omnidirectionally or in a conical pattern ($\sim 60^\circ$) from the ship, the first signal received by the hydrophone may come from a point not normally beneath the ship. These signals which appear as "side" or "ghost" echoes are reflected from promontories off to one side, ahead, or behind the ship.

Also, caution must be exercised in identifying multiple bottom reflections. These reflections, seen in the bottom profile, are generally caused by the entrapment of the signal in the water column, bouncing between the air and seafloor interfaces. Multiples become complex when reverberations between subbottom interfaces are also recorded.

The limitations of the system used must always be considered in interpreting the record. The system's apparent efficiency, for example, is a function of the fundamental frequency present in the received signal and recorder scanning rate. The impedance contrast of the bottom material also has an influence on the apparent efficiency of a system.

Other factors, less controllable, such as ship and water noise, and extraneous 60 cps signals may cause spurious signals on the record.

It is apparent from the above discussion that the interpretation of a continuous seismic reflection record requires the skill and experience of individuals familiar with geologic properties and the capabilities and limitations of the system used.

A certain amount of quantitative information about the nature and physical properties of marine sediments and rocks can be derived from an

analysis of the acoustic properties of the materials. These acoustic-physical property relationships are discussed in subsequent sections.

DATA INTERPRETATION - QUANTITATIVE

Reflection Coefficient

Breslau (1965), Faas (1969), and others have indicated that a correlation exists between the reflective and geologic properties of the seafloor. Smith and Li (1966) have suggested, however, that care should be exercised when attempting to identify sediment type from its reflecting properties, particularly in regions where the sediments may contain a substantial amount of gas.

This section attempts to summarize recent developments in relating the reflection coefficient of the bottom to its sediment or rock type. Knowledge of these quantitative relationships allows the geologist or marine engineer to infer certain properties of the bottom material from a study of the recorded trace or, if a more comprehensive analysis is desired, to use computer data processing techniques to draw quantitative conclusions. The marine construction engineer can make a preliminary estimate of an area's load supporting capabilities, especially if the profiling survey is combined with a limited coring or boring program.

A layered model of the seafloor is composed of strata that are defined in terms of their acoustic impedance (equation (3)). For the case of the incidence of an acoustic wave on a specular reflector, the reflection coefficient is

$$R = \frac{A_r}{A_i} = \frac{\rho_2/\rho_1 - \frac{\sqrt{V_1^2/V_2^2 - \sin^2\theta}}{\sqrt{1 - \sin^2\theta}}}{\rho_2/\rho_1 + \frac{\sqrt{V_1^2/V_2^2 - \sin^2\theta}}{\sqrt{1 - \sin^2\theta}}} \quad (5)$$

where θ = angle of incidence from the normal to the surface (degrees)

For normal incidence, θ is equal to zero; thus equation (5) reduces to

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (6)$$

which was given earlier as equations (2) and (4).

The relationship between losses of acoustic signals attributable to the seafloor and the reflection coefficient is given by the equation for acoustic bottom losses as follows:

$$BL = 20 \log R \quad (7)$$

where BL = bottom loss of a plane wave at normal incidence
(decibels)

The amplitude of the signal received at the hydrophone is dependent on the amplitude of the transmitted signal, the path length of the signal to and from the reflecting horizon, and the reflecting properties of the seafloor. Thus, if it can be assumed that the source signal is constant in at-sea operations—only a compensation due to losses in the water column need to be made. These losses due to transmission through the water column are of two types: spherical spreading losses proportional to $1/L$, where L is the signal path length, and attenuation losses proportional to $e^{-\alpha L}$ where α is the attenuation coefficient of seawater. Thus, two signals, A_1 and A_2 , received by the hydrophones may differ in amplitude due to differences in path length alone without there being a change in bottom conditions (Smith and Li, 1966). That is,

$$\frac{A_1}{A_2} = \frac{L_2}{L_1} e^{-\alpha(L_1-L_2)} \quad (8)$$

In a sufficiently flat area, however, the difference in the losses due to differing path lengths is small and is commonly neglected.

Since sediment porosity is related to bulk density and the reflection coefficient is a function of bulk density, it is possible to establish a relationship between bottom reflectivity (or bottom loss) and porosity (Breslau, 1967).

That is

$$\rho_{sed} = \rho_w n + \rho_s (1-n) \quad (9)$$

where ρ_{sed} = saturated bulk density of sediment (gm/cm^3)

ρ_w = density of seawater (gm/cm^3)

ρ_s = density of sediment solid material (gm/cm^3)

n = porosity of sediment

and (Wood's Equation)

$$V = \left\{ [\rho_w n + \rho_s (1-n)] [\beta_w n + \beta_s (1-n)] \right\}^{-1/2} \quad (10)$$

where β_w = compressibility of seawater ($cm^2/dyne$)

β_s = compressibility of solid material ($cm^2/dyne$)

relate the bulk density, ρ_{sed} , and the acoustic velocity, V , to the sediment porosity, n . From equations (9) and (10), the relationship between reflection coefficient and porosity can be developed. Relationships between porosity and impedances or bottom loss can also be developed. Figure 2 is a plot of the theoretical curves relating porosity with these acoustic properties of marine sediments.

Figure 2 illustrates the linear (approximately) relationship between porosity and sediment reflection coefficient. This relationship has been substantiated by the empirical work of numerous researchers as

$$R = 0.6727 - 0.6961n \quad \text{Hamilton et al. (1956)}$$

$$R = 0.6636 - 0.6478n \quad \text{Sutton et al. (1957)}$$

$$R = 0.6196 - 0.6277n \quad \text{Shumway (1960)}$$

$$R = 0.6634 - 0.6749n \quad \text{Morgan (1964)}$$

$$R = 0.6468 - 0.6456n \quad \text{Faas (1969)}$$

The recent work of Faas (1969) indicates that a 0.97 correlation coefficient exists between reflection coefficient and porosity (Figure 3).

Breslau (1967), in a very comprehensive bottom reflectivity study, obtained a relatively good (0.706) correlation between bottom loss and porosity. Since porosity is related to grain size or textural properties of marine sediments, Breslau (1967) has also established a general relationship between bottom loss and the geological properties of sediments.

Generally, an increase in clay content will increase the sediment porosity because of structural, size and shape effects, and a phenomenon known as bridging (Terzaghi and Peck, 1948). Thus, the net result is that porosity increases as the grain size decreases or as the percentage of silt plus clay increases.

The conclusion drawn by Breslau (1967) and others is that a significant correlation exists between reflectivity of marine sediments and their physical properties, particularly sediment porosity. As in any generalization, caution must be exercised in applying such statements. For example, the reflectivity data noted above have been collected at widely different frequencies, 20 kHz-1 MHz, with no correction for frequency. Since acoustic impedance increases slightly with frequency (Smith and Li, 1966), some correction should be made. Additionally, sediments containing gas derived from the decay of organic matter do not adhere to the above generalizations (Jones, 1962; Smith and Li, 1966). Sediments of this type may be fine-grained and highly porous, yet

excellent reflectors. Such a condition is believed to be caused by these sediments having an acoustic velocity substantially less than that of water (Wood, 1941), in turn causing a large acoustic impedance contrast.

Thus, with the above cautions borne in mind, it is possible to describe the seafloor in terms of either the reflectivity or porosity. The strong correlation between reflectivity and porosity can be used to infer the potential load-bearing properties during a survey; or, if a more quantitative description is desired, computer data processing, either in the laboratory or aboard ship, could be used (Breslau, 1965).

As discussed above, it is feasible to relate porosity to sediment type only in general terms, i.e., high porosity relates to silts and clays, and low porosity to sands and gravels. However, for porosities greater than 55 percent, there is a great overlap in sediment type and precise designations are inconclusive (Smith and Li, 1966; Faas, 1969).

Acoustic Velocity

In order to interpret accurately the continuous seismic reflection record, some knowledge of the acoustic compressional velocity in sediments and rock is required. The seismic record is a time display; in order to estimate sediment or rock thickness, an interval or average velocity for the particular unit must be assumed or measured. Additionally, numerous correlations between the compressional velocities and sediment and rock physical properties have been established. Thus, if the acoustic velocities in the material can be determined, inferences can be made about the expected load-bearing capabilities of this material. This method of remotely determining sediment and rock properties is of particular value in preliminary construction-site surveying work where a large area is to be investigated and, later, in estimating the physical properties of deeply-buried materials, those not sampled using conventional oceanographic corers.

Subsequent sections will summarize current information on acoustic compressional and shear wave velocities in sediments and rock, with an emphasis on the engineering applications of these data.

Compressional Wave Velocity. Marine sediments are porous and loose in structure, having elastic properties which may or may not be directly measured. When this loose aggregate is placed under compacting pressure, the porosity is reduced, the grain-to-grain contact is increased and, as pressure increases, this aggregate acts more and more like an ideal elastic body (Hamilton et al., 1956).

The velocity of acoustic compressional waves in an elastic media is given by Hamilton et al. (1956).

$$V = \left[\frac{3(1-\sigma)/(1+\sigma)}{\beta\rho} \right]^{1/2} \quad (11)$$

Where V = compressional velocity of sound (cm/sec)

σ = Poisson's ratio

β = compressibility of elastic media (cm^2/dyne)

ρ = density of elastic media (gm/cm^3)

or, equivalently

$$V = \left[\frac{k + (4/3)\mu}{\rho} \right]^{1/2} \quad (12)$$

where k = bulk modulus of elasticity (dynes/cm^2)

μ = modulus of rigidity (dynes/cm^2)

If rigidity is lacking ($\mu \approx 0$)

$$V \approx (k/\rho)^{1/2} = (1/\beta\rho)^{1/2} \quad (13)$$

where $k = 1/\beta$

Bulk compressibility of a suspension may be considered as the additive properties of the compressibility of the liquid plus that of the suspended particles, i.e.,

$$\beta = (1-n) \beta_s + n\beta_w \quad (14)$$

where β = bulk compressibility of sediment or elastic media (cm^2/dyne)

n = porosity of the sediment or media

β_s = compressibility of solid material (cm^2/dyne)

β_w = compressibility of seawater (cm^2/dyne)

Similarly, for the sediment wet density

$$\rho = (1-n) \rho_s + n\rho_w \quad (15)$$

where ρ = saturated bulk density of sediment (gm/cm^3)

ρ_s = density of solid material (gm/cm^3)

ρ_w = density of seawater (gm/cm^3)

To determine the thickness of an unconsolidated sediment layer, it is commonly assumed that the velocity in these sediments is nearly equal to that of water (1.5 km/sec). This assumption is accurate, as seen from the data below:

<u>Material</u>	<u>Velocity km/sec</u>	<u>Source</u>
unconsolidated deep-sea sediments	1.6-2.2	Houtz et al., 1968
semi-consolidated deep-sea sediments	1.7-2.9	Houtz et al., 1968
fine sand	1.7	Hamilton et al., 1956
very fine sand	1.6-1.7	Hamilton et al., 1956
silty fine sand	1.5-1.6	Hamilton et al., 1956
medium silt	1.5	Hamilton et al., 1956
clayey fine silt	1.5	Hamilton et al., 1956
clays	1.43-1.70	Sutton et al., 1957
arenites	1.6-1.7	Sutton et al., 1957
lacarenites	1.65-2.77	Sutton et al., 1957

However, as the sediments become increasingly more consolidated, acoustic velocities rapidly increase. Thus, the use of velocity in water for these consolidated sediments may lead to a misinterpretation of layer thickness.

Several methods of determining the true layer thicknesses have been used. An interval velocity for the layer studied may be assumed or it may be calculated from wide-angle reflection (Le Pichon et al., 1968; Clay and Rona, 1965) or seismic refraction methods. (The determination of in-situ sediment velocity will be discussed in a subsequent section.) Also, the interval velocity may be calculated from core-determined values which have been corrected to in-situ conditions (Hamilton, 1963).

Another method of determining layer thickness is to assume or calculate a sound velocity gradient for the material (Hamilton, 1967). Although the sound velocity gradient curve may be exponential in form, a linear curve is commonly assumed. Houtz and Ewing (1963) have used the following equation when the sediment-surface sound speed, average vertical sound velocity gradient, and time of sound travel within the layer are known.

$$h = \frac{V_0 (e^{at} - 1)}{a} \quad (16)$$

where h = sediment layer thickness (km)

V_0 = velocity of sound in sediments at the water-sediment interface (km/sec)

a = average vertical sound velocity gradient within sediment (sec^{-1})

t = one-way sound travel time within sediment (sec)

For deep sea sediments

$$0.5 < a < 2.0 \text{ sec}^{-1}$$

with average, $\bar{a}$, near 1.0 sec^{-1} . Most values, however, lie between 0.9 and 1.4 sec^{-1} (Hamilton, 1965).

Some researchers have described the variation of acoustic velocity with depth with a linear equation of the form

$$V(Z) = V_0 + aZ \quad (17)$$

where $V(Z)$ = compressional velocity of sound at sediment depth Z (km/sec)

Z = depth in sediments (km)

Examples of such equations are:

$$\begin{aligned} \text{shallow water sediments: } V(Z) &= 1.70Z + 1.70 \\ &\text{Nafe and Drake (1957)} \end{aligned} \quad (18)$$

$$\begin{aligned} \text{deep water sediments: } V(Z) &= 0.43Z + 1.83 \\ &\text{Nafe and Drake (1957)} \end{aligned} \quad (19)$$

Besides calculating the sediment-layer thickness, a knowledge of the acoustic compressional velocities is useful in inferring certain physical properties of the sediment and rock. For example, in an analysis of sediments from Lake Erie, Morgan (1969) arrived at the following equations:

$$V = 2.380 - (2.197 \pm 1.208)n + (1.333 \pm 0.982)n^2 \quad r = 0.90 \quad (20)$$

$$V = 2.232 - (1.168 \pm 1.103)\rho + (0.451 \pm 0.333)\rho^2 \quad r = 0.90 \quad (21)$$

where $\rho = \rho_w n + \rho_s (1-n)$

r = correlation between V and n

For marine sediments, relationship between sound velocity and porosity has received considerable attention (Hamilton et al., 1956; Sutton et al., 1957; Nafe and Drake, 1957; Horn et al., 1969). The general conclusion is that sound velocity increases as porosity decreases. Most researchers agree, however, that porosity in itself may be a first approximation of a number of interrelated physical properties that, when combined, affect the sound velocity in sediment. A typical trend of sound velocity relative to porosity is shown in Figure 4.

Since moisture content and void ratio of saturated sediments are functions of available pore space, the curves of these properties should show trends similar to that of porosity when plotted against sound velocity. Figures 5 and 6, taken from Horn et al. (1968), illustrate these trends.

Additionally, there is a positive correlation between wet density and sound velocity in water-saturated sediments—sound velocity increases with increasing wet density (Horn et al., 1968; Sutton et al., 1957; Nafe and Drake, 1957). This correlation is shown in Figure 7.

There is, therefore, a correlation between the acoustic and some physical properties of marine sediments. The higher the porosity, moisture content, and void ratio, the lower is the sound velocity. Increases in wet density are matched by increases in acoustic velocity. There is, however, no readily apparent correlation between sound velocity and dry density, carbonate content or, most unfortunately, shear strength (Horn et al., 1968).

When sediment shear strength is plotted against sound velocity, the data fall into groups which reflect the mean grain size and sediment origin. Although shear strength is not considered to be a reliable index of the acoustic properties of marine sediments (Horn et al., 1968), there is, generally, an increase in sound velocity as shear strength increases.

Grain size is the most important physical property in determining the acoustic properties of marine cores (Horn et al., 1968). For example, turbidites have high velocities, ash layers have intermediate velocities, and muds and clays have low velocities.

Acoustic compressional velocity data may provide an estimate of the facility with which materials may be excavated, i.e., the rippability (Patterson and Meidav, 1965). Granites, for example, have acoustic velocities higher than limestone, and limestone has velocities higher than those in unconsolidated sediments.

Knowing the acoustic velocities of the material also provides the marine construction engineer with a preliminary estimate of the relative bearing capacity of the material. An increase in compressional velocity generally implies an increase in the firmness of the material and, hence, an increase in its relative bearing capacity (Patterson and Meidav, 1965). Seismic information plus soil mechanics tests can be of immense value in the evaluation of slope stability and subgrade behavior.

There are, of course, limitations and dangers in the engineering interpretation of seismic velocity data. Foremost, perhaps, is that in the highly saturated sediments immediately underlying the water column, acoustic velocities may be equal to or less than the acoustic velocity in water (Jones, 1962; Morgan, 1969). The explanation for an anonymously low acoustic velocity in the sediment is the presence of gases derived primarily from the decay of organic matter (Jones, 1962) or the following explanation quoted from Morgan (1969): "Adding solid particles to water (decreasing the porosity) increases the bulk density without an appreciable change in compressibility (see equation (13), i.e., $V = (1/\beta\rho)^{1/2}$ Wood's equation given earlier); hence, decreasing the velocity. However, upon a further decrease of porosity, the system assumes a grain-to-grain contact and, consequently, the compressibility decreases. The compressibility change seems to dominate the bulk density change, causing the seismic velocity to increase. The data show such behavior down to a porosity of about 0.75."

A small amount of gas greatly increases the average compliance of the material without significantly affecting the average density of the sediment (Wood, 1941). A velocity in the mixture less than that of either constituent is possible.

Shear Wave Velocity. Since the shear wave velocity is relatable to shear strength parameters of a material, the measurement of its velocity would be of immense value to the marine construction engineer.

Shear waves are propagated through marine sediments; but, there are considerable practical difficulties in the measurement of its velocity. Most seismic equipment, for example, is sensitive to the energy of a wave and does not discriminate between the arrival of a shear or a compressional wave. Further, since shear waves do not generally propagate through a liquid to any marked degree, the transducer recording shear wave behavior needs to be near to or on the seafloor (Auld et al., 1969). Also, normally the coefficient of rigidity of the sediments is so small that measurements by direct timing of recovered samples have been accomplished only under high pressure.

Laughton (1957) measured shear wave velocities in a sample of globigerina ooze compressed between porous disks. Shear waves were observed at pressures of 500 kg/cm^2 on the initial compression. On decompression, however, shear waves could be identified at pressures as low as 64 kg/cm^2 .

Nafe and Drake (1957) compiled indirect information on shear wave velocities in marine sediments from seismic refraction measurements (Figure 8).

More recently, Auld et al. (1969) have measured average shear wave velocities of marine sediments off northern California using an ocean bottom seismometer. The resulting values are 0.34-0.40 km/sec for the average shear velocity, results which are consistent with values obtained in earlier studies to explain the dispersion of oceanic surface waves (Sykes and Oliver, 1964; Oliver and Dorman, 1961).

Swain (1962), in an engineering site evaluation study for the Bay Area Rapid Transit Tunnel in San Francisco Bay, used seismometers in boreholes to arrive at in-situ values of shear velocity. The in-situ values differed substantially from the values measured on cores taken at the same locations.

The shear wave velocity data, therefore, are meager. It is strongly suggested that research into the methods and the feasibility of shear wave velocity measurements in marine sediments be undertaken because of the enormous engineering significance of these data.

Elastic Moduli and Acoustic Velocities. The relationship between elastic moduli and longitudinal and shear velocities are

$$V_p = \sqrt{\frac{E_d(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} = \sqrt{\frac{K + (4/3)\mu_d}{\rho}} \quad (22)$$

$$V_s = \sqrt{\frac{E_d}{2(1+\sigma)}} = \sqrt{\frac{\mu_d}{\rho}} \quad (23)$$

where V_p = compressional wave velocity (cm/sec)

V_s = shear wave velocity (cm/sec)

σ = Poisson's ratio

K = bulk modulus or incompressibility
= $1/\beta$ (dynes/cm²)

β = compressibility

μ_d = dynamic rigidity (shear modulus)(dynes/cm²)

E_d = modulus of elasticity (Young's Modulus)
(dynes/cm²)

ρ = saturated bulk density (gm/cm³)

and

$$\sigma = \frac{1/2 (v_p/v_s)^2 - 1}{(v_p/v_s)^2 - 1}$$

$$K = \rho (v_p^2 - (4/3)v_s^2)$$

$$\mu_d = \rho v_s^2$$

$$E_d = 2\mu_d(1+\sigma)$$

The above relationships between elastic moduli and compressional and shear wave velocities are not entirely valid for marine sediments since they are not truly elastic. However, if it is desirable to determine the dynamic elastic properties of the material at the frequency of the seismic wave, as in the vibratory testing of foundations for machinery or runways, the above equations are precise (Meidav, 1962).

When long-term static loading of unconsolidated material must be considered, the rheological effects of creep and flow must be taken into account if the response of the body to stresses is to be completely specified (Meidav, 1962; 1960). This would require the inclusion of one or more viscosity coefficients describing the behavior of the material under low frequency or static conditions.

This frequency effect upon the rigidity coefficient is similar to the response of water to shear waves. At low frequencies, shear waves will not pass through the water because of near zero rigidity; however, at megacycle frequencies, shear waves do propagate because of a finite, discernible rigidity.

Meidav (1960; 1962) considers the standard linear solid a better model of the stress-strain relations in the earth, i.e.,

$$\sigma + T_0 \frac{d\sigma}{dt} = \mu_0 (\epsilon + T_1 \frac{d\epsilon}{dt}) \quad (24)$$

where σ = stress

ϵ = strain

T_0, T_1 = relaxation time

μ_0 = operator dependent upon the type of wave used

The ratio of phase velocities in a standard linear solid/elastic is given by (Meidav, 1962)

$$\frac{\text{standard linear solid}}{\text{elastic}} = \frac{2}{\left\{ \frac{1 + \omega^2 T_0 T_1}{1 + \omega^2 T_1^2} \right\} \left\{ 1 + \left[1 + \frac{(\omega(T_0 - T_1))^2}{1 + \omega^2 T_0 T_1} \right]^2 \right\}^{1/2}} \quad (25)$$

where ω = angular frequency

An equation of the above type may be capable, according to Meidav, of accounting for the changing values of elastic moduli with frequency, which may be troublesome in unconsolidated materials, and for the fact that dynamic moduli are often higher, sometimes considerably higher, than the static values. Swain (1962), for example, calculated a Poisson's ratio of 0.275 from laboratory tests on a core; and 0.343 for an in-situ value using compressional and shear wave velocities. Nafe and Drake (1961) indicated that seismic refraction data commonly yield values of Poisson's ratio higher than 0.25.

Whitman (1969), however, commented that measurements of elastic moduli in-situ using geophysical techniques have, in a number of cases, been found to be in excellent agreement with those values determined by laboratory tests.

Further, geophysical measurements are made under very small strains; and sediments may experience nonlinear behavior, as shear strain in soil increases above 10^{-6} inch/inch (Whitman, 1969). Thus, a value of Poisson's ratio calculated from seismic techniques may not be adequate for foundation calculations where considerably larger shear strains are involved.

It is not intended to discuss comprehensively the rheological properties of marine sediments. The reader is referred to such works as Meidav (1960) for further details. It is, however, evident that much more study is needed to determine the extent to which the moduli of marine sediments, particularly clay, are frequency and level-of-shear-strain dependent.

Meanwhile, seismic methods do provide an approximate value of Poisson's ratio which would be of value in assessing the in-situ behavior of materials.

Determination of Sound Velocity in Sediments. The techniques most commonly used to determine the velocities of sound in unconsolidated sediments and rocks are the wide-angle reflection, seismic refraction, and the common depth point techniques.

In the wide-angle reflection technique, the separation of the sound source and the hydrophone is steadily increased so that the angle between the incident and reflected waves progressively increase. Recently, expendable sonobuoys have been used so that sediment velocities can be determined while reflection profiling (Le Pichon et al., 1968). The method of determining the interval velocities by the wide-angle reflection profiling

techniques has been extensively described (e.g., Dix, 1955; Clay and Rona, 1965). The basis of this method is the familiar T^2 versus X^2 equation of reflection seismology:

$$T^2 = T_o^2 + \frac{X^2}{V^2} - 2T_o \frac{X}{V} \sin \phi \quad (26)$$

where T_o = vertical reflection time

T = reflection time at distance X from the source

V = interval velocity in layer

ϕ = slope of lower interface with respect to upper interface

If D is the arrival time of the direct wave to the sonobuoy and V_H is the horizontal water velocity

$$T^2 = T_o^2 + \frac{D^2 V_H^2}{V^2} - \frac{2T_o D V_H}{V} \sin \phi \quad (27)$$

If we assume that the interfaces of the layers are parallel ($\phi = 0$), the above equation reduces to

$$T^2 = T_o^2 + D^2 \left(\frac{V_H^2}{V^2} \right) \quad (28)$$

which is an equation of a straight line in D^2 and T^2 . The interval velocity is determined, therefore, by the inverse of the slope.

More sophisticated analyses utilize least-square curve-fitting approaches and computer techniques. For example, in the manner of Clay and Rona (1965), the odd powers of X disappear for horizontal layers so that the T^2 versus X^2 equation becomes

$$T^2 = T_o^2 + \frac{1}{V_{an}^2 X^2} + KX^4 \quad (29)$$

where V_{an} = inverse of slope of T^2, X^2 line at the origin

K = constant

from which the following equation is derived

$$V_n^2 = \frac{(V_{an}^2 T_o - V_{an-1}^2 T_{on-1})}{(T_{on} - T_{on-1})} \quad (30)$$

where V_n = interval velocity for nth laver

If the hydrophone and sound source are separated by a sufficiently large distance, sound waves are refracted at the seafloor and underlying interfaces. These refracted waves travel at greater speeds through the rock and are again refracted through the water to the receiving hydrophone. In practice, the extended hydrophone cable is gradually hauled in while a record is being made. Initially, the refracted waves arrive before the direct waves, but the difference in arrival times becomes smaller as the cable length is decreased. The reciprocal of the slope of the refracted arrival record, time versus distance, is the velocity. For a comprehensive discussion of this method, see a standard geophysics text, as Dobrin (1960).

Another method for determining sound velocities through sediments is the common depth point (CDP) method (Hempstead, 1966). This technique, widely used by the petroleum industry, involves the recording of reflections at different surface detectors from different shot positions which are chosen to maintain the same reflecting points on the subsurface reflectors. The results yield a time-varying primary and multiple velocities. Computers are generally required in processing the data. See Mayne (1965, 1962, 1967) for excellent discussions of this method.

Many other sophisticated techniques developed primarily for use in petroleum exploration have been utilized, such as Automatic Velocity Analysis (AVA) and Visual Interval Velocity Approximation (VIVA) (Petty Geophysical Engineering Company).

Thus, there are several methods to determine the compressional velocity profiles in marine sediments. Of the methods discussed, it is believed that wide-angle reflection profiling using sonobuoys is the most attractive approach for engineering purposes.

The measurement of shear wave velocities, whether in-situ or on cores, is much more difficult. Devices with probes (Shumway, 1960) and bottom-sitting seismometers (Auld et al., 1969) have been used with some success. This area requires much more research, in particular with emphasis upon the engineering applications and interpretation of the data.

Attenuation of Sound Velocity

Knowledge of the attenuative properties of sediment types enables the person interpreting a seismic record to "say something" quantitative about the nature of the material present on the basis of its being a

"good" or a "poor" reflector of sound. Although experience in interpreting many seismic records is, admittedly, the best teacher, it is believed that quantitative information about the attenuation properties of sediments is useful, if only to serve as a primer to those individuals inexperienced in such analysis.

A number of researchers have performed attenuation measurements on marine sediments. Shumway (1958, 1960) measured attenuation for a number of sediment samples in the frequency range 20 to 40 kHz. Hampton (1967) made a series of attenuation measurements on artificial sediments over frequency range of 4 to 200 kHz. Wood and Weston (1964) obtained attenuation data in muds over a frequency range of 4 to 72 kHz. Cole (1965) calculated attenuation coefficients for various seafloor sediments from reflectivity for frequencies below 4 kHz.

McCann and McCann (1969) published a very comprehensive article in which the attenuation mechanism in marine sediments was described.

There are three ways in which energy may be dissipated from a plane wave propagating through a water-saturated sediment.

1. Rayleigh scattering
2. solid friction (particle-particle) losses
3. viscous (particle-fluid) losses

Rayleigh scattering losses, characterized by a dependence on the fourth power of frequency, are negligible for sediments of mean diameter less than 0.1 cm at frequencies less than 1 mHz (Nolle et al., 1963).

Solid-friction losses, which occur at the points of contact between the particles, are characterized by a linear variation of attenuation coefficient with frequency over a frequency range from 1 to 10^8 Hz (Attewell and Ramana, 1966; McCann and McCann, 1969). The physical mechanism of this loss does not appear to be well understood at this time.

Viscous losses arise because of the acoustic velocity differential between the solid particles and the fluid in the sediment. McCann and McCann (1969), using their own and Shumway's (1960) experimental data, have theoretically defined the ranges of sediment particle size over which each of the latter two mechanisms is dominant. Their results will be summarized.

Figure 9 is a plot of the computed (McCann and McCann, 1969) and experimental values of attenuation coefficient against sediment mean diameter at a frequency of 30 kHz. It can be seen that attenuation coefficient increases with increasing mean diameter up to a value of about 0.006 cm.

According to McCann and McCann (1969), the attenuation for sediments of mean diameter less than 0.0017 cm may be calculated from the equation below assuming that the clay particles and water behave together as a fluid of density 1.35 gm/cm³ and viscosity of 0.015 poise.

$$2\alpha = ck_n(\sigma_d - 1)^2 \frac{s}{\{s^2 + (\sigma_d + T)^2\}} \quad (31)$$

where c = volume concentration of particles

α = attenuation coefficient

$k_n = \omega/c_c$ = wave number

$\sigma_d = \rho_s/\rho_f$

where ρ_s = density of particles

ρ_f = density of suspending fluid

$$s = \frac{9}{4r_p \sqrt{\omega/2\nu}} \left\{ 1 + \frac{1}{r_p \sqrt{\omega/2\nu}} \right\}$$

$$T = 0.5 + 9/(4r_p \sqrt{\omega/2\nu})$$

r_p = particle radius

ν = kinematic viscosity of the fluid

ω = angular frequency

c_c = velocity of compressional waves through the suspension

Therefore, viscous dissipation of the compressional waves occur. The theory is valid from experimental evidence for the frequency range 30-370 kHz.

For sediments of mean diameter greater than 0.0017 cm, the attenuation coefficient is given by the sum of a viscous term plus a solid friction term as

$$2\alpha = K_1 f + K_2 f^{1/2} \quad (32)$$

where K_1 , K_2 are constants and f is the frequency (kHz)

In the artificial circumstances of zero overburden pressure and a very well-sorted sediment, the viscous mechanism may dominate; for "real" sediments at a depth of burial of 2 m, the solid-friction mechanism is dominant (McCann and McCann, 1969).

Thus, in general, fine-grain sediments attenuate acoustic energy to a lesser degree than coarser matter. Therefore, sound may penetrate clays and silts more deeply than sand or gravel. This result, of course, is what is commonly observed.

Other Acoustic Methods for Determining Seafloor Properties

There are other methods of acoustically deriving information about the physical and load-bearing properties of the seafloor, but these methods have not been researched to the degree that the acoustic reflectivity, velocities, and absorption have been.

The Mine Defense Laboratory has developed a Sea Bottom Classifier (SBC) which determines the softness of a sea bottom by measuring the elongation of reflected acoustic pulses using a standard depth sounder (Stanley, 1968). If a short narrow-beam acoustic pulse is transmitted into a hard bottom, the received echo is about the same length as the transmitted pulse. On the other hand, in a soft bottom the acoustic pulse penetrates the bottom, and volume reverberation within the bottom causes elongation of the echo pulse proportional to pulse penetration.

Another approach employs a frequency analysis of the bottom-reflected pulse. The frequency content of the pulse, as determined through a Fourier analysis, may contain information which correlates with the physical or engineering properties of the sediment.

SUMMARY AND CONCLUSIONS

The continuous reflection profiling system provides detailed geological information about a potential seafloor construction area, as well as quantitative data about its potential load-bearing capabilities.

The marine construction engineer is supplied with a more accurate and a continuous profile of the subbottom geology than may be obtained using only borings and depth sounding techniques. Core and borehole data may be correlated with the seismic record. (Note here the immense potential value of using the NCEL Seafloor Deep Corer with a seismic survey.)

In foundation studies, competent strata, sediment, and bedrock are mapped. Slumping, faulting, and other geologic features are located. Differential compaction of overburden, sediment erosion and deposition (scour and fill), and filled channels are among the other geological features which may be delineated. Continuous reflection profiling, in short, provides information from which a detailed and accurate geologic map of a potential construction area can be constructed.

Additionally, the records are useful in the planning of excavation, dredging, and other engineering tasks which require knowledge of the "rippability" and trafficability of an area.

To properly interpret a seismic record to gain knowledge of the physical and load-bearing properties of marine sediments, the acoustic properties of the material must be known. Sediment reflectivity (or bottom loss) is strongly correlated with sediment porosity; thus, with due caution exercised, reflectivity may indicate the sediment type present: high porosity implies silts and clays, low porosity implies sands and gravel.

The acoustic compressional velocity for a sediment type is required to calculate the overburden thickness accurately from a reflection record. Additionally, acoustic velocities also correlate with some of the physical properties of marine sediments, in particular sediment porosity and bulk density: generally, sound velocity increases as porosity decreases. Correlations have also been established between acoustic velocity and moisture content, void ratio, and saturated bulk density. Although acoustic properties are not considered to be a reliable index of the shear strength of marine sediments, there is, generally, an increase in sound velocity as shear strengths increase.

Acoustic velocities also provide an estimate of the facility with which material may be excavated ("rippability"). Granites, for example, have velocities larger than limestone, and limestone has velocities larger than those in unconsolidated sediments.

An increase in compressional velocity generally implies an increase in the firmness or the relative bearing capacity of a material.

Shear wave velocities of sediments, much more difficult to measure than compressional velocities, are related to the shear strength parameters of the sediment and, therefore, of immense value to the marine construction engineer. Furthermore, if the compressional and shear wave velocities are known, the dynamic elastic properties of the material, such as Poisson's ratio, can be calculated.

Although the in-situ determination of shear wave velocities requires bottom-sitting instruments as seismometers or probes, the determination of in-situ compressional velocities is relatively simple. Standard seismic refraction measurements or the more feasible techniques of wide-angle reflection may readily be used.

In addition to a knowledge of the acoustic reflectivity and velocities, information about the acoustic attenuation properties of marine sediments is of value. The attenuation coefficient, in general, increases with an increase in the mean diameter of the sediment grains; therefore, the

fine-grained sediments, clays and silts, attenuate acoustic energy to a lesser degree than coarser materials. Sound may, therefore, penetrate clays more deeply than sands.

Continuous reflection profiling can be, therefore, a most useful tool for the marine construction engineer. Most importantly, the technique provides a detailed, accurate, and continuous profile of the subsurface geology not arrived at through other, more conventional techniques. Secondly, seismic methods and a knowledge of the acoustic properties of marine sediments provide quantitative data of the relative load-bearing properties of a region.

RECOMMENDATIONS FOR FUTURE RESEARCH

It is suggested that research applicable to marine construction engineering application be pursued in the following areas:

1. Measurement of shear wave velocities in-situ and on cores.
2. In-depth study of the rheological properties of marine sediments, including the relationship of the dynamic Poisson's ratio (from seismic wave velocities) to the static value; and the relationship of Poisson's ratio at small (seismic) stresses to realistic, operating stresses.
3. Comprehensive analysis of the information of engineering value contained in the bottom-reflected pulse.
4. Investigate the feasibility and applicability of other, nonacoustic remote methods to obtain rapid information about the characteristics of a potential seafloor construction site, with the aim to develop a complete, rapid, and accurate site survey system.
5. Design and fabricate a deep towable (to 6,000-foot depth), self-powered 3.5 kHz seismic reflection profiler for obtaining data over small, test sites. A seismic sound source towed near the seafloor will provide high resolution whether the echo events are picked up near the source or at the surface. A self-powered source using surface hydrophones would require no electrical cable but could be towed by synthetic line.

It would appear that this (number 5) would be the most cost-effective approach towards advancing the state-of-the-art in profiling technology by providing a simple device to retrieve high-resolution, seismic reflection data from great depths for the construction engineer.

Figure 1. Schematic diagram of continuous profiling system. (From Schlank, 1968.)

Figure 2. Theoretical curves of density, velocity, impedance, and reflection coefficient as related to porosity. (From Breslau, 1967.)

Figure 3. The relationship between sediment porosity and reflection coefficient as measured by various researchers. Also shown is the common regression line with the 99 percent confidence limits. (From Faas, 1969. Used by permission.)

Figure 4. The relationship between sediment porosity and compressional velocity of sound in sediments. (From Horn, Horn, and Delach, 1968. Used by permission.)

Figure 5. Moisture content versus velocity. (From Horn, Horn, and Delach, 1968. Used by permission.)

Figure 6. Void ratio versus velocity. Note that sound speed remains almost constant for sediments having void ratios from 6.00 to 2.25. Lower void ratios are marked by increases in sound velocity. (From Horn, Horn, and Delach, 1968. Used by permission.)

Figure 7. Saturated bulk density versus velocity. Points that fall in a group at the center of the figure represent a core which is unique in that it is predominantly volcanic glass and ash. (From Horn, Horn, and Delach, 1968. Used by permission.)

Figure 8. Variation with depth of compressional wave velocity (V_p) and shear wave velocity (V_s) for shallow and deep water sediments. The compressional velocities are average curves representing the seismic refraction data. The shear velocities are derived from the compressional velocities by means of a velocity-porosity relation. (From Nafe and Drake, 1957. Used by permission.)

Figure 9. Computed and experimental values of compressional wave attenuation as a function of sediment mean diameter at a frequency of 30 kHz. (From McCann and McCann, 1969. Used by permission.)

Appendix A

PRELIMINARY SPECIFICATIONS FOR A SURFACE-TOWED SUBBOTTOM PROFILING SYSTEM SUITABLE FOR MARINE CONSTRUCTION ENGINEERING APPLICATION

For marine civil engineering applications, it is desirable to have a high-resolution subbottom profiling system yet also capable of transmitting sufficient power so that subbottom penetration is achieved in water depths to at least 6,000 feet. A frequency of approximately 3.5 kHz may suit resolution needs as energy at this frequency will resolve reflecting layers about 0.5 m apart. Minimum penetration desired is 200 to 300 feet in unconsolidated sediment in 6,000 feet of water.

With the above admittedly general and somewhat arbitrary guidelines in mind, some preliminary specifications of this desired subbottom profiling system can be considered.

The continuous reflection profiling system shall be an operationally complete system composed of the following:

1. transducer in a V-fin or other towed configuration
2. high power transceiver in splash-proof and shock-proof case for portable operation
3. precision recorder in splash-proof and shock-proof case for portable operation
4. connecting cables
5. instruction manuals

A transducer utilizing a resonant frequency of 3.5 kHz shall be furnished. Acoustic signal output of the unit shall be a short pulse of 1 to 2 cycles (at 3.5 kHz) duration. Rise time and ring time shall be small ($<100\mu\text{sec}$). The acoustic source level shall be sufficient to provide 200 to 300 feet of penetration in a muddy bottom in 6,000 feet of water. The transmitted beam width shall be 30 degrees or less. The transducer element shall be tested to a maximum working depth of 500 feet of water. Maximum weight of the transducer and V-fin shall not exceed 500 pounds.

The transmitter section of the transceiver shall provide power output sufficient for the above bottom penetration (200 to 300 feet, muddy bottom, 6,000 feet of water) at a frequency of 3.5 kHz. Pulse widths shall be variable and selectable by a panel with selections for 5, 10, and 20 milliseconds. A solid state transmit/receive switch shall be used. Output short circuit and overvoltage protective breakers shall be provided.

Input circuit protection for the receiver section of the transceiver shall be provided. Minimum detectable input signal to the receiver shall be no greater than 0.5 microvolts rms. Maximum receiver gain shall be not less than 100 db and continuously adjustable by a manual panel control. Supplementary time variable gain control (TVG) circuits shall be provided.

The recorder shall be a high resolution dry or wet paper type unit. Full time sweeps of 1/16, 1/8, 1/4, 1/2, 1, 2, and 5 seconds shall be selectable by a panel switch, or be of the fully programmable type. The stylus drive system shall be a solid state system having no gears and shall provide accuracies of 0.1 percent of full scale. Paper feed drive shall be by a stepping motor providing a variable marking density which is controlled by a panel control. Scale lines on all ranges shall be generated by a precision clock electronic timing system providing accuracies of 0.01 percent of full scale. Marking intensity shall be continuously variable from light grey to intense black. Event markers are to be recorded by manual operation of a panel button or switch, with external jacks for hookup to external circuitry.

Ten cycles of programming shall be provided for manual operation with selected periods of transmit, receive or gate. A flashing warning light indicating low paper shall be located on the panel; the record display area shall be illuminated with a white light.

Connecting shielded cables, complete with matching connectors for installation to the equipment, shall be provided.

A comprehensive descriptive information of all components and units of the equipment and conditions of warranty shall be furnished.

A competent field technician or engineer shall demonstrate and instruct in the operation of the complete system aboard a survey vessel under actual operating conditions and effect the adjustments in the system to performance standards. NCEL shall provide the vessel in the vicinity of Port Hueneme, California.

The entire system shall be completely operable from an AGOR class vessel (AGOR-12 or 13, as standard).

Satisfactory and acceptable performance of the equipment shall include a clear bottom and subbottom record along a profile ranging in water depth from 10 to 1,000 fathoms at a speed of 10 knots. Bottom penetration of 200 feet of a muddy bottom in 6,000 feet of water is the minimum performance acceptable.

Appendix B

PRELIMINARY ENGINEERING COMMENTS ON COMMERCIAL SUBBOTTOM PROFILING SYSTEMS

The author has made a preliminary investigation of the capabilities of current continuous reflection profiling systems from manufacturers' specifications, users' comments, and at-sea experience with an emphasis on their suitability for the marine engineering applications. No attempt will be made to summarize each system's operating capabilities and specifications: the reader is referred to the excellent study by Schlank (1968). Furthermore, the opinions expressed in this section are those of the author alone and in no way are to be interpreted as the expressed or implied opinion of the Naval Civil Engineering Laboratory or the U. S. Navy.

It appears that, to the best of the author's knowledge, no presently available commercial subbottom system meets all the specifications drawn in Appendix A. Perhaps the system best approximating the specifications is the large-transducer Edo-Western 3.5 kHz Model 400. The transducer for the Model 400 is difficult to tow; records may be poor in shallow (<600 feet) water; resolution is less because several cycles of energy are transmitted. Perhaps some of these deficiencies could be remedied.

An alternative approach would be to use two commercial systems, a high and a low resolution system, in lieu of one "do everything" system, the combination of which should meet the majority of engineering needs.

Since a sparker system is standard equipment aboard the USNS BARTLETT (T-AGOR-13) and it is assumed that this vessel, or one with similar equipment, will be used by the Navy in marine survey applications, this sparker system provides a deep penetration, low resolution capability.

In conjunction with the sparker system, and to provide a high-resolution capability, it is suggested that a small-transducer 3.5 kHz subbottom system similar, but not limited, to the Edo-Western Model 415, Ocean Research Equipment Model 1036, or equivalent, be used. The sparker system would provide low-resolution about the geological setting while the 3.5 kHz system would supply the high-resolution information on the sediment structure.

There are, nevertheless, limitations on the operating conditions of the small-transducer 3.5 kHz systems. These high-resolution systems, for example, generally give satisfactory performance in continental shelf depths (<600 feet); certainly not meeting any requirements of 6,000 feet.

To obtain satisfactory high-resolution performance in deep (~6,000 feet) water, a higher powered system such as the large-transducer Edo-Western Model 400, the EG&G High Resolution BoomerTM, or similar would have to be used.

Thus, in summary, the one system best approaching the specification delineated in Appendix A is, in the author's opinion, the large-transducer Edo-Western Model 400 3.5 kHz system. In lieu of using this system, it is suggested that (1) for continental shelf depths, a small-transducer 3.5 kHz high-resolution system plus the sparker be used, and (2) for depths greater than 600 feet, the High Resolution BoomerTM, Edo-Western Large-Transducer Model 400, or like, plus the sparker be utilized.

Much of the compromise between penetration and resolution in deep water discussed here can be obviated by deep-towing a small-transducer, 3.5 kHz, piezoelectric sound source near the seafloor.

Surveys of this type have been limited to special applications requiring high resolution in oceanic depths, or the location of buried objects in deep water. The initial cost on such equipment is modest and, although sea operations are slow, very high resolution (0.5 m) and good penetration (>100 feet) of the unconsolidated sediment column in deep (>6,000 feet) water is provided.

Both Edo-Western and Ocean Research Equipment (ORE) Companies, for example, provide components for deep-towed, or submersible-mounted application. The SEACON site's seismic reflection profiler survey was provided by a 5 kHz submersible-mounted system.

Appendix C

LIST OF SYMBOLS

A_1	Amplitude of signal received through path length L_1 (dyne/cm ²)	r	Correlation between V and n
A_2	Amplitude of signal received through path length L_2 (dyne/cm ²)	r_p	Radius of particle (cm)
$\bar{a}$	Average vertical sound velocity gradient within sediment (sec ⁻¹)	T_0	Vertical reflection time
A_i	Amplitude of incident signal	T	Reflection time at distance X from the source
A_r	Amplitude of reflected signal	t	One-way sound travel time within sediment (sec)
BL	Acoustic bottom loss (decibels, dB)	Δt	Difference between arrival times of the reflected wave fronts
c	Volume concentration of particles	V	Compressional velocity of sound or interval velocity in layer (cm/sec)
c_c	Compressional wave velocity through suspension (m/m sec)	V_{an}	Inverse of slope of T^2, X^2 line at the origin
D	Arrival time of direct wave to sonobuoy	V_H	Horizontal velocity in seawater
d	Distance between reflecting layers (m)	V_n	Interval velocity for n th layer
E_d	Modules of elasticity (dynes/cm ²)	V_p	Compressional wave velocity (cm/sec)
f	Frequency (kHz)	V_s	Shear wave velocity (cm/sec)
h	Thickness of sediment layer (km)	V_0	Velocity of sound in sediments at the water-sediment interface (km/sec)
K_1, K_2	Constants	V_1	Compressional velocity of sound in medium 1 (cm/sec)
K	Bulk modulus or incompressibility (dynes/cm ²)	V_2	Compressional velocity of sound in medium 2 (cm/sec)
k	Bulk modulus of elasticity (dynes/cm ²)	$V(Z)$	Compressional velocity of sound at sediment depth Z (km/sec)
k_n	Wave number	v	Velocity of sound in water (≈ 1500 m/sec)
L_n	Signal path length (m) through path n	X	Distance from source
n	Porosity of sediment or elastic media		
R	Reflection coefficient		

(continued)

Z	Depth in sediments (km)	ρ_w	Density of seawater
Z ₁	Acoustic impedance of medium 1 (gm/cm ² sec)	ρ_1	Saturated bulk density of medium 1 (gm/cm ³)
Z ₂	Acoustic impedance of medium 2 (gm/cm ² sec)	ρ_2	Saturated bulk density of medium 2 (gm/cm ³)
Z _n	Acoustic impedance of medium n (gm/cm ² sec)	σ	Poisson's ratio or stress
α	Attenuation coefficient of seawater	σ_d	Ratio of density of particles and of suspending fluid
β	Compressibility of elastic media (cm ² /dyne)	T ₀ , T ₁	Relaxation time
β_s	Compressibility of solid material (cm ² /dyne)	ϕ	Slope of lower interface with respect to upper interface
β_w	Compressibility of seawater (cm ² /dyne)	ω	Angular frequency
ϵ	Strain		
θ	Angle of incidence from the normal to the surface (degrees)		
μ	Modulus of rigidity (dynes/cm ²)		
μ_d	Dynamic rigidity (shear modulus) (dynes/cm ²)		
μ_o	Operator dependent upon the type of wave used		
ν	Kinematic viscosity		
ρ	Saturated bulk density of sediment or density of elastic media		
ρ_f	Density of suspending fluid		
ρ_n, ρ_{sed}	Saturated bulk density of sediment (gm/cm ³)		
ρ_s	Density of solid material		

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13. ABSTRACT Seismic Reflection Profiling (SRP) data of value to the seafloor engineer include: (1) sediment ("soil") thickness, (2) sediment structure, (3) the slope of the bedrock beneath the sediment layer, (4) bedrock topography, if sufficient tracklines are run to permit contouring, (5) bedrock structure, if penetration permits, and (6) acoustical data from which certain physical, engineering, and load bearing properties of an area can be approximated. Qualitative interpretations of acoustical data are made as a matter of course by the experienced analyzer of SRP records and include such parameters as: (1) echo intensity from the seafloor and subbottom interfaces, indicating hard (high reflectivity) and soft (low reflectivity) layers, (2) penetrability of the seafloor (in unconsolidated sediments) is generally inversely proportional to grain size, (3) point return, or discrete hyperbolic echo returns, indicative of large irregularities compared to the sound frequency recorded such as boulder beds, or a weathered bedrock surface. Quantitative interpretations of seismic reflection data include the measurement of compressional wave velocities by underway wide			

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angle reflection techniques. Compressional sound velocities, however, do not give unambiguous solutions to sediment types. Since the shear strength of the sediments is related to the shear wave velocities, its measurement would be of immense value to the seafloor engineer. If the compressional and shear wave velocities are known, the dynamic elastic properties of the material, such as Poisson's ratio, can be calculated. Shear waves, though transmitted by saturated marine sediments, are not propagated through the water column and so are unavailable to surface, or even deep-towed acoustic surveys.

When both the compressional wave velocity and the reflectivity coefficient of a stratum are known, the bulk density can be calculated. The precise measurement of reflection energies, termed the reflection coefficient, have been attempted with some success, but sediment types cannot consistently be categorized, even broadly as clay, silt, or sand, largely because of the rather widespread phenomenon of surficial sediment-entrapped gas which produces a too-high reflection coefficient for the host sediment.

Three approaches to the problem are indicated: (1) the development of shear wave determination techniques for a rapid measurement of sediment shear strength, (2) a more comprehensive and quantitative analysis of the information of engineering value contained in the bottom-reflected pulse, and (3) the development of a deep-towed, high-resolution subbottom profiler.

Shear wave measurements cannot be made underway, disqualifying this approach for site reconnaissance purposes.

The second approach is being pursued, notably at the Naval Undersea Research and Development Center, San Diego, California, and jointly by Raytheon Company-University of New Hampshire.

The third approach has not been vigorously pursued due primarily to the limited number of potential users. The requirement to conduct sub-bottom profiling over small construction sites in water depths to 6,000 feet is not widespread and so has been bypassed by industry.

It is proposed that a self-powered, deep-towed subbottom profiler be designed and fabricated which will produce high resolution records of at least the first 100 feet of soil in water depths to 6,000 feet.

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