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July 1993

Dredging Research Technical Notes

A Rapid Geophysical Technique for Subbottom Imaging

Purpose

This technical note describes the low-noise, high-resolution subbottom imaging system developed to remotely and efficiently determine characteristics of subbottom marine sediments as they relate to dredging. The theoretical foundation of this approach, which is based on acoustic impedance, is described. A case history survey of Galveston Ship Channel is also summarized.

Background

The focus of this work, conducted by the Dredging Research Program, is toward developing a technique to remotely and efficiently determine characteristics of subbottom marine sediments as they relate to dredging. A low-noise, high-resolution subbottom imaging system is essential to this program. To fulfill this requirement, a digital data acquisition system has been combined with specialized processing software to accurately assess bottom and subbottom in situ conditions.

These undertakings respond to the fact that, each year, the U.S. Army Corps of Engineers spends millions of dollars on river and harbor maintenance and ship channel realignment projects. Currently, the Corps relies on drilling and laboratory testing programs to assess marine sediments in terms of material type, density, and thickness for purposes of characterizing proposed dredging sites. However, sampling and coring programs are costly, provide only discontinuous information about material characteristics, and cannot effectively address situations where actual subbottom conditions are highly variable.

Additional Information

This technical note was written by Mr. R. F. Ballard, Jr., Mr. K. J. Sjostrom, Mr. R. G. McGee, and Mr. R. L. Leist. For additional

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Theoretical Foundation

The acoustic impedance method is a modification of the seismic reflection technique commonly used in offshore oil exploration but tailored to shallow-water environments. As energy generated from an acoustic source (in the form of a plane wave) arrives at a boundary between two layers of differing material properties, part of the energy will be reflected back toward the surface and part transmitted downward. Portions of the transmitted energy will undergo absorption or attenuation in the layer while the remainder propagates through to the next stratigraphic boundary. Ratios between transmitted and reflected energy, called reflection coefficients, are dependent on the density and velocity of the materials through which the energy is propagating.

Wave velocities are controlled by elastic properties of the two-phase sediment mass (sea water in pores and mineral structure). Properties such as porosity and grain size affect sound velocity only through their effects on the elasticity of the sediment. In previous studies (Hamilton 1970, 1972), it was concluded that elastic properties of water-saturated sediment could be expressed through Hookean elastic equations, unless attenuation is considered, in which case linear viscoelastic equations are recommended.

The basic equation for the velocity of a compressional wave V_p is

$$V_\rho = [\,(k + 4/3\mu)/\rho\,]^{1/2} \tag{1}$$

where

k = incompressibility or bulk modulus and equals $(1/\beta)$
β = compressibility
μ = shear (rigidity) modulus
ρ = saturated bulk density

When a medium lacks rigidity, Equation 1 becomes

$$V_\rho = (\kappa/\rho)^{1/2} \tag{2a}$$

or

$$V_\rho = (1/\beta\,\rho)^{1/2} \tag{2b}$$

Compressibility β and density ρ in Equation 2b have been expanded into

$$V_\rho = \left(\frac{1}{[\eta\beta_w + (1 - \eta)\beta_s]\,[\eta\rho_w + (1 - \eta)\rho_s]} \right)^{1/2} \tag{3}$$

where η is the volume of pore space occupied by water (fractional porosity) and subscripts s and w indicate mineral solids and water.

The influencing parameters of this basic seismic wave equation suffice to answer the question *Why acoustics to characterize bottom/subbottom materials?* To continue, the acoustic reflection coefficient (R) is defined as

$$R = \sqrt{\frac{E_R}{E_I}} \tag{4}$$

where

E_R = reflected energy
E_I = total energy incident to the boundary (see Figure 1)

The reflection coefficient is also equal to

$$R = \frac{(Z_s - Z_w)}{(Z_s + Z_w)} \tag{5}$$

where

$Z_w = \rho_w C_w$ = water impedance
$Z_s = \rho_s C_s$ = soil impedance
$\rho_w = 1\ \text{g/cm}^3$
$C_w = 150{,}000\ \text{cm/sec}$

Hence, it is clear that the acoustic impedance (Z_s) of the surficial layer can be calculated readily. ***The product of transmission velocity and density of material is the acoustic impedance*** and represents the influence of the material's characteristics on reflected and transmitted wave energy. The relationship between acoustic impedance and specific soil properties has been empirically based on an extensive database of world averages of impedance versus sediment characteristics (Hamilton 1970, 1972; Hamilton and Bachman 1982) (see Table 1).

Table 1. Soil Classification Versus Acoustic Impedance Range (Hamilton 1972)

Description	Acoustic Impedance, $\frac{\times 10^{2}\,\text{g}}{\text{cm}^{2}/\text{sec}}$
Water	1,450
Silty clay	2,016-2,460
Clayey silt	2,460-2,864
Silty sand	2,864-3,052
Very fine sand	3,052-3,219
Fine sand	3,219-3,281
Medium sand	3,281-3,492
Coarse sand	3,492-3,647
Gravelly sand	3,647-3,880
Sandy gravel	3,880-3,927

Note: Values corrected for temperature and salinity.

At this point, it must be emphasized that Hamilton's pioneering efforts were limited to ***surficial*** bottom materials. To extend the depth of investigation into multilayer subbottom environments, Caulfield and Yim (1983) devised a model correlating to Hamilton's work. The model is used to correct for absorption and other losses in bottom sediments as a function of frequency so that the reflection coefficients and acoustic impedance of sediments can be calculated as if they were surficial sediments (reflectors). In practice, the concept is extended to each subsequent layer until the signal-to-noise ratio is at a level from which information cannot be extracted with accuracy (normally 5 db). The model is then combined with classical multilayer reflection mathematics to yield reflection coefficients equivalent to surficial sediments for subbottom layers. Since some assumptions must be made regarding attenuation factors (determined from site-specific borings and laboratory data), this approach *must be defined as empirical.*

Equipment

A seismic source of known energy content as a function of frequency, deployed just below the water surface, generates acoustic waves that propagate downward through the water column and sediments. High-resolution profiling systems specifically designed for shallow-water use and operating at frequencies below 12 kHz are typically used. As a rule, lower operating frequencies allow greater energy penetration into the subbottom, but because of longer wavelengths, lack the vertical resolution of higher frequency systems.

Two commercially available geophysical instruments, a 3.5-kHz "pinger" system and an integrated, high-definition 400-Hz to 5.0-kHz "boomer" system, are normally used to fulfill the above criteria. Recently, tests with chirpers have been conducted to assess potential advantages. However, data discussed herein were obtained with the more conventional "pingers" and "boomers." As transmitted energy from these seismic sources propagates through sediment of varying densities and acoustic velocities, energy is reflected at geologic boundaries where there is a distinct contrast in the acoustic impedance between layers. Reflected signals are amplified, filtered, and recorded with a specially designed shallow seismic, digital data acquisition system developed in conjunction with Caulfield Engineering (Caulfield 1991a). Energy loss as a function of frequency is then determined. The system also provides real-time presentation of the seismic signal for acquisition quality control.

Data Acquired and Ground Truth Comparisons

Because of the nonuniqueness of seismic reflection signatures, several combinations of geologic conditions could conceivably yield similar signal characteristics and computed impedance values. In specific geologic regions such as the Mississippi Sound, Savannah Ship Channel, or San Francisco Bay, differing sediment units usually have a characteristic and relatively narrow range of impedance values. Therefore, using calibration procedures that incorporate local core and laboratory data, seismic reflection data are processed at known sample locations to yield acoustic impedance values of the known reflection horizons.

Estimates of in situ density are derived from computed impedance values and correlated with ground truth information. Acoustic predictions versus core data for consolidated materials in Mobile and Gulfport Ship Channels was presented by Ballard, McGee, and Whalin (1992). Results documented were within 1 percent.

Similar findings have also been observed when comparing acoustic impedance density predictions to nuclear densitometer data for fluff/fluid mud type materials in the Gulfport Ship Channel. Again, correlation has been excellent. A continuing program of database expansion, coupled with ground truth information obtained using a wide variety of conditions, is necessary. Testing to date has shown that density estimates to within 5 percent of in situ values are obtained (Ballard and McGee 1991, McGee and Caulfield 1991).

A plot of the impedance function versus laboratory measurements of density from core samples taken in the Mississippi Sound is presented in

Figure 1. Hamilton's data (represented by the solid line in Figure 1), although obtained along the shelf and slope of the continental terrace, show remarkable agreement.

At this point it should be noted that none of the above data were processed by matched filter correlation procedures. Marked improvements in data resolution have been noted since signal correlation has been implemented. This subject will be discussed in more detail later.

Case History

During summer 1992, an acoustic impedance survey of Galveston Ship Channel was conducted. Although several objectives were accomplished, the phase concerning volumetric determinations of "dirty" sands (density 1.7 to 1.95 g/cm^3) underlying the proposed channel were of specific interest because of their potential use for beaches. The following discussion presents the methodology used to locate, identify, and quantify that material of interest to the U.S. Army Engineer District, Galveston.

Data Acquisition

In the normal course of data acquisition, field records related to amplitude of recorded signal, time, and distance provide the geophysicist/ engineer with quick-look assessments of data quality and subbottom conditions. Data are oftentimes dually recorded by analog and digital systems. Analog presentations are usually in shades of gray, while digital data are

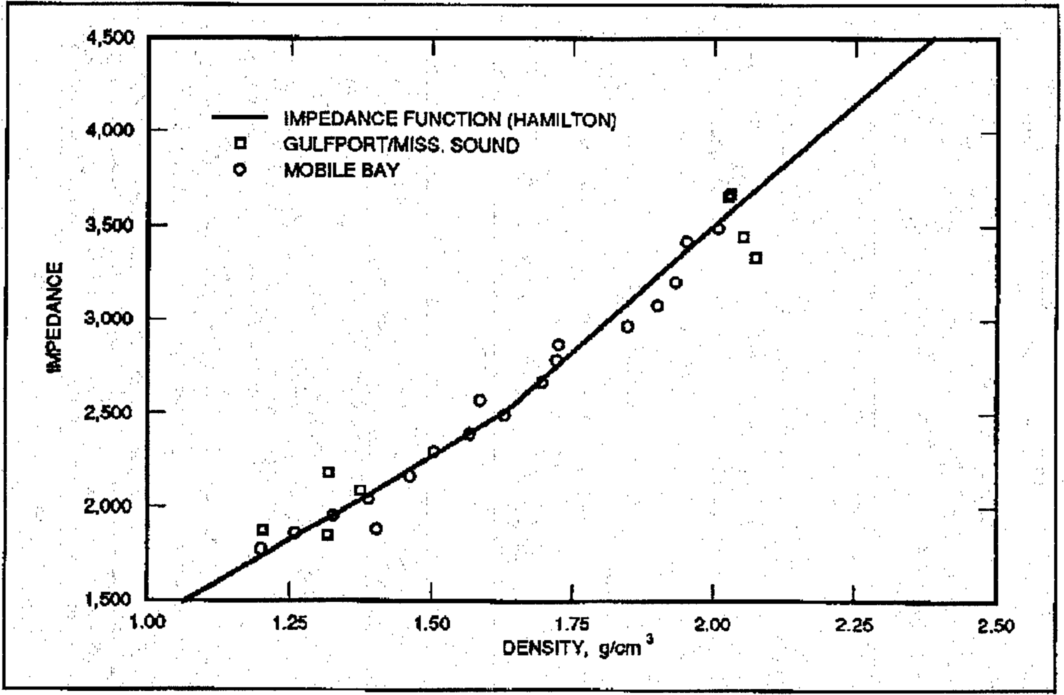

Figure 1. Computed impedance versus in situ density compared to Hamilton (1972)

displayed in color. Figure 2 is a typical 3.5-kHz pinger amplitude cross section obtained in Galveston Ship Channel. Note that the top of the graph is not the water surface, but an assigned water column delay. This offset allows full vertical expansion of the subbottom display, which in this case extends into the subbottom more than 40 ft. Changes in stratigraphy are readily apparent. Records of this type are used as quick-look guidance in boring placement.

Upon determination of the reflection coefficients and impedance function at known locations, the virtually continuous seismic profiles are processed. The single-channel, digitally recorded data are read into the processing software developed with Caulfield Engineering (Caulfield 1991b) and corrected for transmission losses due to spherical spreading and compensated for absorption losses in each layer. Further data enhancement is accomplished by use of recently developed (Caulfield 1992) matched filter signal correlation processing. Use of the new correlation procedures has resulted in signal-to-noise ratio improvements of at least 10 db.

Correlation processing also allows for identification of the frequency characteristics of source signals and noise, and provides techniques to optimize source and array selection, thus improving frequency penetration recovery. This has resulted in vertical resolution improvement, reduced noise contamination, and improved ability to target special materials or objects.

Classical multilayer algorithms are used to compute equivalent reflection coefficients and impedances along the profile. This in turn provides density estimates of shallow subbottom layers and classifies the lithostratigraphy (Hamilton 1972, Caulfield and Yim 1983). The results are corrected for tidal fluctuations and correlated with survey positioning data. Processed results are presented in the form of annotated amplitude cross sections or two- and three-dimensional (3-D) views, color-coded according to material density.

Density Predictions

By incorporating the virtually continuous coverage of subbottom materials with digital terrain modeling techniques, rapid and accurate computations can be made of volume and material type to be removed by dredging. Furthermore, a detailed database has now been established for project monitoring and long-term planning. Computed sediment densities within the project area can be displayed in a color-coded, 3-D view as shown in Figure 3, if desired by the user. In this example, lighter shadings are indicative of less dense material; the darkest are analogous to densities 1.7 g/cm^3.

Displays of this type provide much-improved data interpretation and visualization for the end product user as compared to standard two-dimensional presentations generated exclusively from boring information.

However, caution must be exercised by the user to maintain an awareness of real data versus computer-generated extrapolations.

Volumetric Calculations

Before computer-assisted volume estimates can be calculated, a continuous 3-D computer model of the subbottom data must be generated for each survey line. In addition, a 3-D perspective model (Figure 3) consisting of a composite of data from all individual survey lines may be created for use in modeling proposed channel cuts, evaluating slope stability, and so forth. At the project planner's discretion, he may elect to view an area of interest from various angles or create different displays by stripping or slicing at any desired coordinate.

Using Figure 3 for our example, the volume of any material to be removed can be easily calculated. This example will predict the configuration of silty ("dirty") sands (>1.7 g/cm^3 density; 2,864 to 3,052 × 10^2 $g/cm^2/sec$ acoustic impedance) underlying a selected segment of the project study area. Calculating the volume of material present within a selected area of the perspective model is accomplished by calculating the volume of material present within the corresponding area of each profile line model.

In our example, the profile line model shown in Figure 4 corresponds to the section of the 3-D perspective model (Figure 3) nearest the viewer. Note that the axes labels in Figure 3 show northing and easting coordinates, while the axis label in Figure 4 reflects relative feet from start-of-line. This conversion is necessary to correlate the profile line models to amplitude records that are plotted with locations relative to start-of-line.

Before calculating volumes, the area of interest must be sliced out of the computer model and the material density range to be displayed selected. In this example, the volume of material present in the area between the bottom to -55.0-ft depth, and between 3,000 and 7,000 ft from start-of-line, having a density of >1.7 g/cm^3, will be selected. The section of the model below -55 ft is stripped away, and the sections from 0 to 3,000 ft and from 7,000 to 19,000 ft would be sliced from the display, as shown in Figure 5.

Finally, the density of material to be displayed would be set to >1.7 g/cm^3. Calculations based on these parameters are then computer-generated and displayed, as shown in Figure 6, yielding an estimated volume of 167,366 cu yd of "dirty" sand (materials >1.7 g/cm^3) within the specified boundaries. This step is repeated for each profile line model within the area of interest, summing the estimated volumes for an overall project volume total.

Conclusions

In its present state of development, acoustic impedance processing of seismic reflection data provides an accurate, continuous description of bottom and subbottom marine sediment characteristics in a rapid, cost-effective manner. Results from properly calibrated surveys have been used to provide Corps Districts and dredging contractors with

- Density estimates of marine sediments.
- Continuous subbottom information for planning and designing dredging and sampling programs.
- Estimates of the volume and type of material to be removed through dredging.
- A detailed and continuous geologic database for aiding long-term planning of future work.

Acoustic impedance information, if properly implemented in the project planning stages, provides valuable data on the distribution and extent of differing marine sediments, aids in locating optimal placements of sampling cores, and supplements previously obtained soil borings by providing continuous profile coverage of sediment characteristics between sample locations.

Epilogue

During preparation of this technical note, plans were formulated to perform high-resolution acoustic impedance surveys prior to dredging operations in Boston Harbor, Baltimore Harbor, and Houston Ship Channel. Additionally, an acoustic survey is being planned to locate gravel beds in the Atchafalaya River.

Possibly for the first time in Corps of Engineers history, the Mobile District advertised site conditions for dredging at Gulfport Ship Channel using density predictions determined by geophysical acoustic impedance surveying in addition to traditional bore hole information. True site conditions, resulting from dredging operations begun in May 1992, have been closely monitored and compared to predictions. Results, as reported by Mobile District inspectors and dredging contractor Bean, have been excellent.

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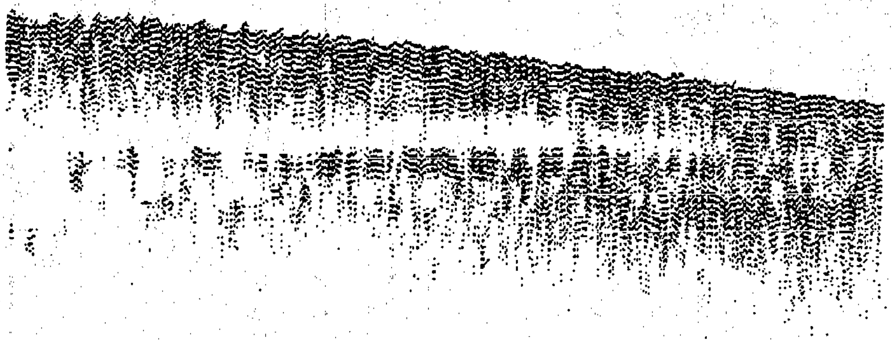

Figure 2. Pinger (3.5-kHz) amplitude cross section, Galveston Ship Channel

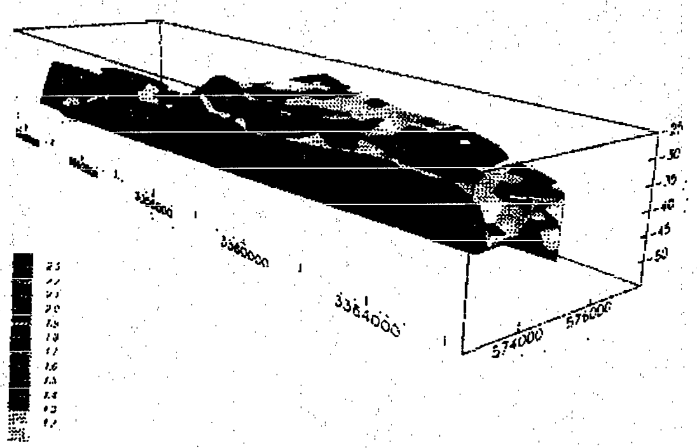

Figure 3. Three-dimensional perspective view of inner bar and anchorage basin, Galveston Harbor. Axes are displayed in northing and easting coordinates

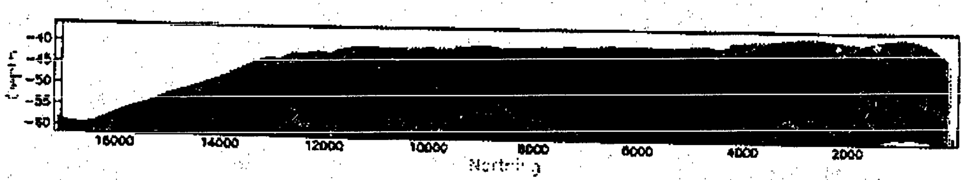

Figure 4. Full profile model

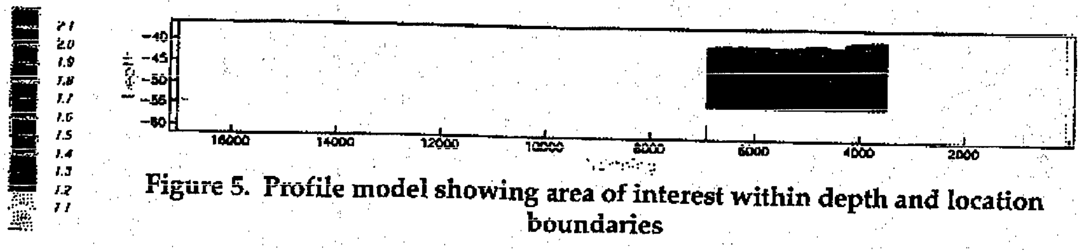

Figure 5. Profile model showing area of interest within depth and location boundaries

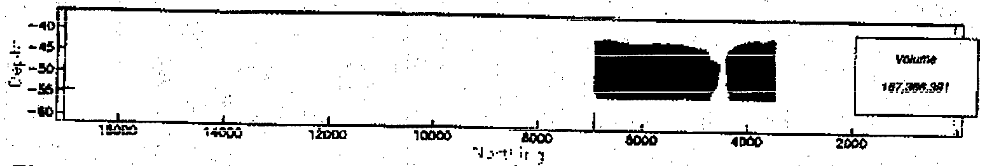

Figure 6. Profile model showing only material 1.7 g/cm^3 density within area of interest