UNH SEA GRANT PROGRAMS

UNH-RAYTHEON SEA GRANT PROJECT

SECOND ANNUAL PROJECT REPORT
(June 1971 - June 1972)

The Science and Technology of Utilizing the Bottom Resources of the Continental Shelf

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A Cooperative University-Industry Research Project

between

University of New Hampshire Durham, New Hampshire 03824	Raytheon Company Portsmouth, Rhode Island 02871

UNIVERSITY of NEW HAMPSHIRE
DURHAM, NEW HAMPSHIRE. 03824

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A SECOND YEAR PROGRESS REPORT TO
THE NATIONAL SEA GRANT PROGRAM
OF
THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

THE SCIENCE AND TECHNOLOGY OF UTILIZING THE BOTTOM RESOURCES OF THE CONTINENTAL SHELF

A COOPERATIVE UNIVERSITY-INDUSTRY RESEARCH PROJECT

2ND ANNUAL REPORT

(Second Annual Report Covering Grant No. DC 1-36114)

JUNE, 1971 TO JUNE, 1972

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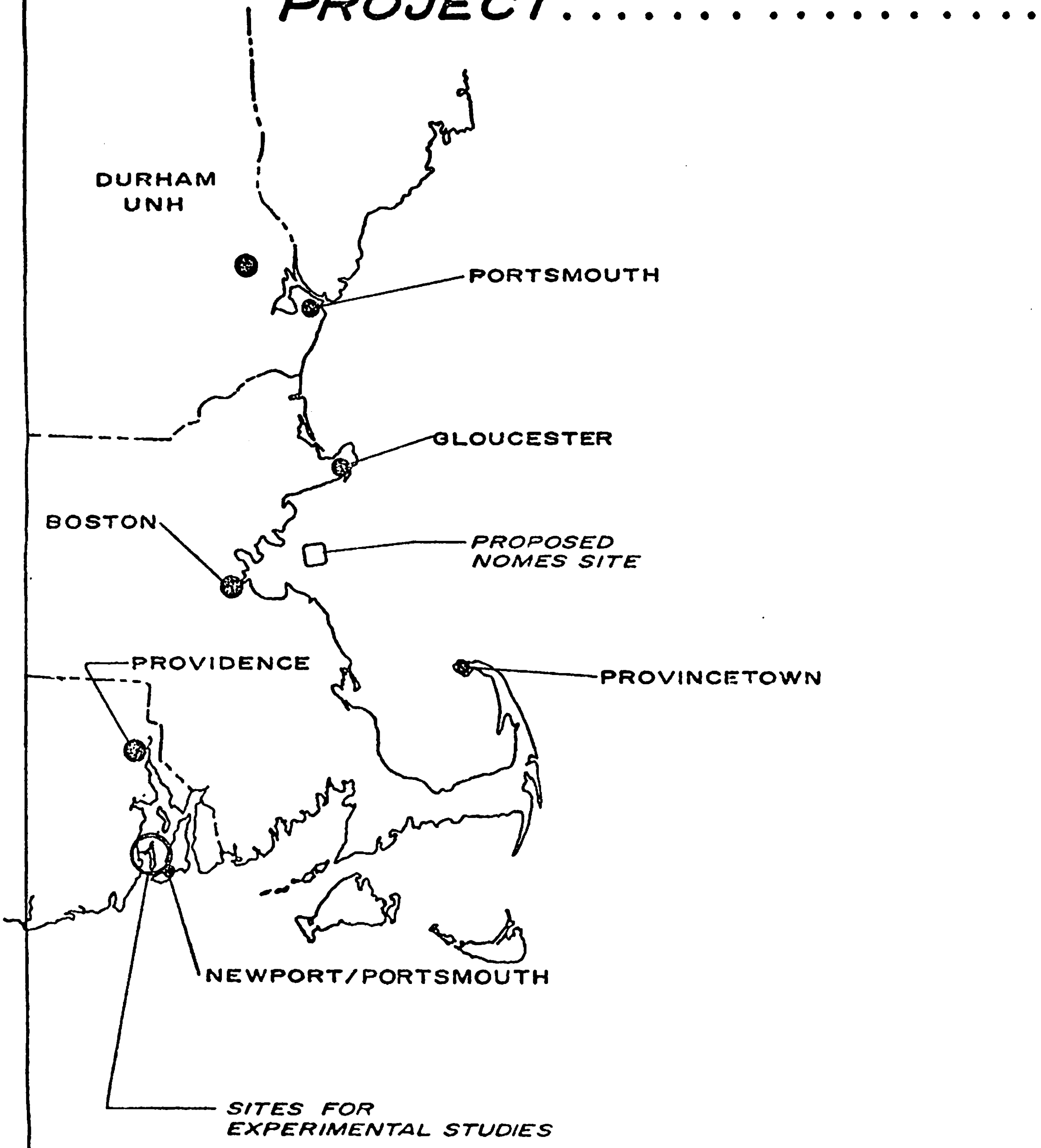
THE GEOGRAPHY OF UNH–RAYTHEON SEA GRANT PROJECT....................



ACKNOWLEDGEMENTS

The UNH-Raytheon project team of faculty, students and industrial colleagues are grateful to the National Sea Grant Program for support and encouragement of this research project, through Grant No. DC 1-36114. The financial support from the Raytheon Company and the University of New Hampshire also is gratefully acknowledged.

The constructive and helpful review by colleagues outside the cooperating institutions has been excellent, and is an important source of information which has substantially aided this program of research. We are particularly grateful to Dr. E. L. Hamilton for his valuable suggestions and his experimental data, and to those colleagues who attended our progress review meeting in January 1972.

We also wish to acknowledge the efforts of our colleagues listed in Appendix IV who have contributed so extensively to the progress reported herein. The project is indebted also to Dr. R. Steven Jenks for his contribution to the project during the leave of absence of one of the co-principal investigators.

Robert W. Corell - Project Manager

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

This document is the second in a series of annual reports to the National Sea Grant Program of the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce. The report covers a university/ industry research and development project with two major thrusts: (1) to develop effective technologies to acoustically classify and assess the coastal sea floor and subbottom sediment for both physical and engineering properties, and (2) to study from a broad perspective the technical, ecological, legal and economic understandings essential to a responsible exploration and utilization of a country's continental shelf bottom resources. The report summarizes the objectives and accomplishments for the second year and discusses these results in the context of a five-year research and development effort.

Technical progress in six specific areas is discussed.

1. The development of field theoretical models which predict the inter-actions of acoustic energy with a liquid viscoelastic (ocean - subbottom) media.

2. The results of computer studies to develop predictors of subbottom characteristics and to corroborate the model with actual subbottom soils data.

3. The acquisition and analysis of soil mechanical data is presented.

4. The acquisition and analysis of a substantial set of acoustic signatures taken over subbottoms which have been sampled for soil mechanical data is described.

5. Initial thinking regarding a system to survey coastal bottom areas is presented.

6. The initial activities and results from an Environmental/ Ecology impact study of nearshore mining of sand and gravel is discussed and plans for a long-term study (NOMES)* are presented.

The impact of the research effort upon the two participating institutions is discussed, including a summary of experience gained from this complex inter-institution research efforts.

The plans for the third year of the project are outlined, and an overview of the forthcoming NOMES project is presented. A summary listing of accomplishments is given, along with supporting appendix material.

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* New England Offshore Mining Environmental Study

I. BACKGROUND AND OBJECTIVES FOR THE UNH-RAYTHEON SEA GRANT PROJECT

Historical Perspectives

In the Spring of 1970 the National Sea Grant Program began supporting an University/Industry Research and Development Project to work towards the creation of an effective acoustic technology to classify and assess the coastal sea floor and subbottom sediments for both physical and engineering properties. The inter-institutional research project was conceived as a timely response to national needs for study from a broad perspective of the technical, ecological, legal and economic understandings essential to responsible exploration and utilization of a country's continental shelf bottom resources. Overall project objectives developed in the initial proposals*, [1,2,3] are summarized here:

1) To develop means of acoustically measuring sea floor parameters of predictive or assessive value that relate directly to the extraction of resources and to the implantation of structures on the continental shelf. By providing a deeper understanding of the nature of the subbottom aggregate, a more responsible policy for protection, preservation, and rational use of the continental shelf can be developed.

2) To develop a prototype system model for responsible exploitation of the continental shelf that will integrate remote acoustic sensing, rapid analysis, ecological and related technology with the legal and economic implications. This prototype model will be designed to permit rational, technical and business judgments to be made involving the uses of the continental shelf.

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* The superscript denotes references listed in the References Section of this report, located in Appendix I.

3) To develop a total management system which may successfully support and coordinate applied research, conducted jointly by university, industry and public agencies.

4) To stimulate and direct cooperative experiments with interested parties to employ the system models in extraction or implantation programs.

5) To establish a research and development project as a tool, among others, to educate students in scientific methodologies in engineering with career interests in the applied aspects of ocean technology.

These broad project objectives were conceived within the context of three specific technical goals to be accomplished during the life of the project. The research and development activities of the faculty, graduate/undergraduate and professional associates at the University of New Hampshire and the technical personnel of the Submarine Signal Division of the Raytheon Company are directed toward developing and creating:

1) Technologies which significantly aid in the location, identification and extraction of coastal mineral deposits, with an initial effort directed toward coastal sand and gravel deposits.

2) Technologies which add to our ability to identify the structural properties of the coastal ocean bottom necessary in the design and construction of structures supported by the sea floor.

3) An understanding of the influence that exploitation of offshore sedimentary resources may have upon the environment and upon society.

These broad project objectives and specific technical goals were developed in the context of a five-year research and development project. A detailed overview of the project can be obtained by reviewing the Task Flow Chart (Figure 1) which, while published in the initial proposal, still

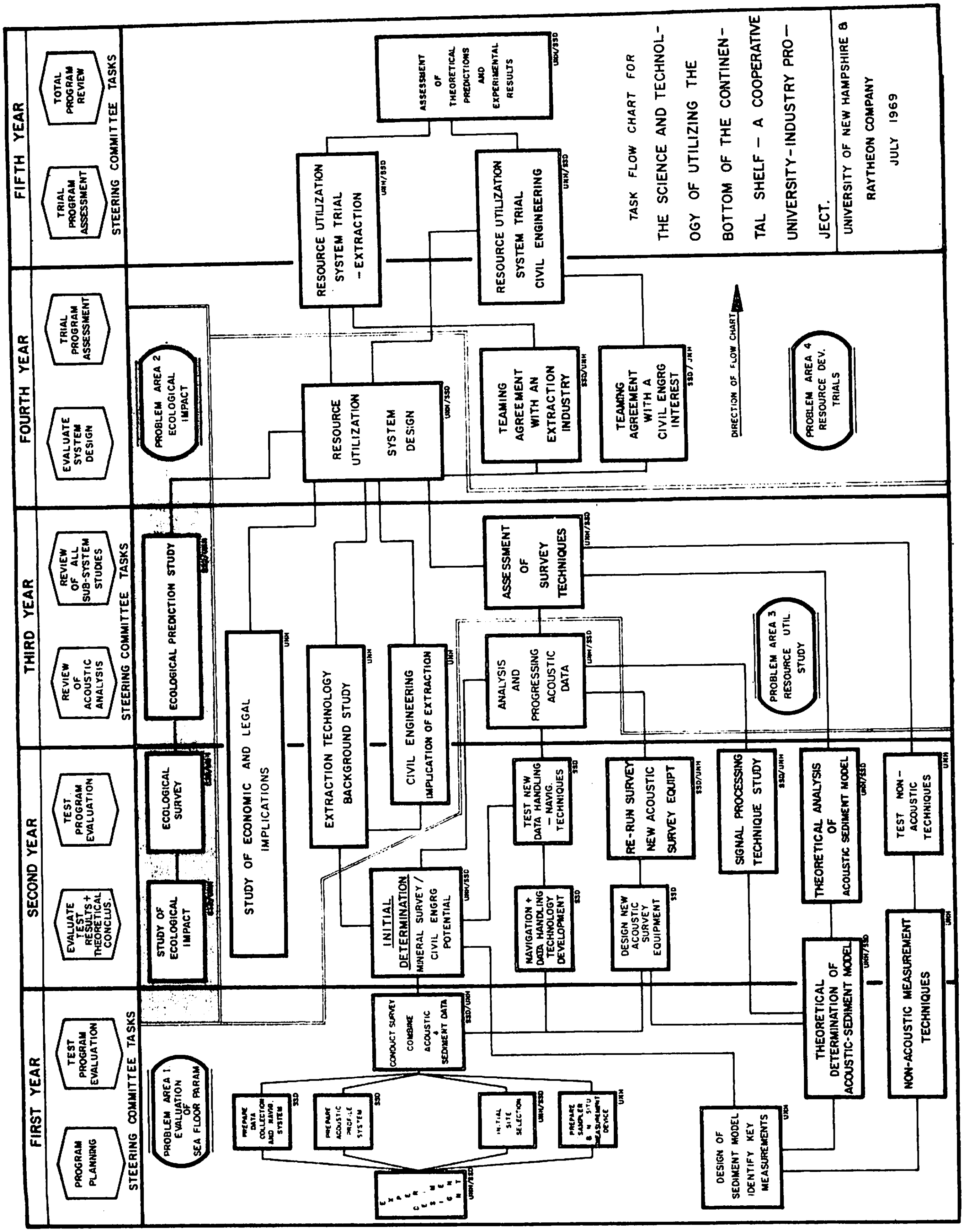

Figure 1

UNH-Raytheon Sea Grant Project Four Year Task Flow Chart depicts quite accurately the project task goals. We believe the scope and potential impact that these objectives and goals suggest have broad implications. As stated in the original proposal[1], "The targets chosen for this study have ramifications that extend beyond the specific purposes that are stated in the proposal. It is evident that by-products in both research and technology will develop that touch almost every federal agency that deals with the ocean, most of the institutions involved in the Sea Grant Program, and many industrial activities. . . The gains to the nation from a successful program would be many. The development of the continental shelf will be greatly enhanced if one can remotely obtain a meaningful and inexpensive description of the physical properties and the load-bearing characteristics of marine sediments." After two years of work, we continue to hold to the perceptions that guided us in writing these optimistic and somewhat presumptious words. The specific objectives and accomplishments for the first year were discussed in the First Annual Report on Progress.[4] The specific objective and accomplishment from the second year are the subject of this report.

Second Year Objectives

The detailed objectives for the second year of the project were fully outlined in the proposal which preceded the second year grant.[5] An overview of these objectives can be seen in the Task Flow Chart (Figure 1). For completeness, more detailed summary of the second year objectives follows:

1) Continued development of theoretical/mathematical models which can improve our understanding of the relationship between acoustic signatures and the physical properties of the ocean bottom and interface.

2) Conduct experiments at sea which are guided by the insights gained during the first year's activities so as to acquire improved acoustic and soil mechanical data. These data are essential to the analytical models and to the development of new technologies.

3) Continued development of a prototype acoustic data acquisition system.

4) Initiate research on the environmental impact of coastal mining activities to assess: 1) the potential effect upon benthic and pelagic species and their habitants and the alteration of the habits of marine species resulting from increased turbidity and/or excessive siltation caused by the mining of marine sand and gravel deposits, and 2) the effects upon other marine resources (e.g. fisheries) caused by removal of mineral resources (e.g. offshore sand and gravel deposits).

5) Continue to study and improve our understanding of multi-institutional research and development collaboration.

6) Continue to integrate the research and development activities into the on-going educational and academic goals of the University and the business/industrial objectives of the industry in the project.

The specific technical goals for the second year were discussed in detail in the second year proposal[5], and can be summarized as follows:

1) <u>Model Development</u>: Continued development of the acoustical soil mechanical model (a field-theoretical model based upon multi-layer techniques) so as to include porosity effects in the subbottom, reverberation effects caused by hydrodynamic fluctuations, distortion of sound caused by subbottom inhomogenities and surface roughness, and to begin to look critically at non-linearities in the subbottom. The single layer model and the formalism for an n-layered model are to be completed

during the second year (See Appendix II for additional detail).

2) Model Corroboration: Evaluation of theoretical predictions from the field-theoretical model against acoustic and soil mechanical data acquired at sea together with initiation of parametric and sensitivity studies (See Appendix II for additional details).

3) Soil Mechanics and Geomorphology: Improved core sampling system and establish improved core analysis techniques. Efforts will be directed toward establishing relationships between the descriptive parameters for marine soils and the acoustic signatures. Additional core samples from selective sites will be acquired (See Appendix II for additional details).

4) Signal Processing and Data Acquisition: An acoustic data bank, with data in both digital or analog form will be established. Studies will be conducted using classical filter theory which consider the statistical character of the received acoustic signatures and which include noise field considerations. The program will be expanded to include Kalman-type filtering for n-layered systems (See Appendix II for more details).

5) Systems/Technology Development: Initial design studies will be conducted to develop prototype exploration technologies for the location and classification of coastal marine resource deposits.

6) Environmental/Ecology Impact: Long-range planning for an experimental dredging operation will be started, along with the testing and establishment of methods for determining the ecological impact of such an experiment. The details of

of a "before-during-and-after" dredging study will be thoroughly considered.

A Summary Outline of the Second Annual Report

The report which follows reviews the research team's accomplishments during the period June, 1971 to June, 1972. It is offered as a general summary, relying on specific technical papers and similar documents to provide discussion for the interested specialist. These materials, many of which are listed in Appendix I, are available from the project manager.

This report is divided into five major sections:

I. Background and Objectives for the UNH-Raytheon Sea Grant Project - Discusses the essential background and historical material necessary to an understanding of the report.

II. Technical Progress During Second Year of Activities - Covers each major technical area and describes in summary form the activities of that area of research.

III. Management and Inter-Institutional Aspects of the Project - Presents an overview of the impact of the project upon the two participating institutions, and an overview of this University/industry project.

IV. Perspectives for the Third Year - Provides a summary of the proposed activities for the third year of the project, including the development of the New England Offshore Mining Environmental Study (NOMES Project).

V. Accomplishments and Summary of Activities - Provides a summary listing of the accomplishments and a summary of activities of the project for the second year.

II. TECHNICAL PROGRESS DURING SECOND YEAR OF ACTIVITIES

Introduction

The technical emphasis within this project during the second year has maintained two themes, first the development of the basic science and technology for the identification and classification of soil mechanical properties by a combination of remote acoustic surveys and physical testing of marine soils, and second, the initiation of an environmental/ecological impact study of in-situ conditions surrounding actual recovery of sand and gravel deposits. In general, the second year objectives as outlined in Section I of this report have been accomplished. In some of these areas we are significantly ahead of our projected schedule. In some areas we lag behind. This is due to an adaptation of our priorities as a consequence of opportunities that have developed or due to changes in actual funding. We expect the project will meet the general objectives of the five-year **program** as originally established.

Each of several technical areas are summarized in this report since details on many aspects of the project are contained in engineering reports, thesis, technical publications, conference papers, and internal memoranda. These are referenced wherever appropriate. In all cases, corroborating data is available, and interested investigators are encouraged to contact us for more details.

The project, during the past year, has concentrated principally upon the following major areas, which serve also as an outline for the remainder of this section of the report:

1) Acousto-Soil Mechanical Model Development;

2) Computer Analysis and Model Corroboration for Theoretical Analysis;

3) Soil Mechanics and Geomorphology;

4) Signal Processing of Experimental Acoustic Data;

5) The Development of Exploration Systems/Technology;

6) Environmental/Ecology Impact of Nearshore Mining of Sand and Gravel.

Acousto-Soil Mechanical Model Development

Early in the project it was recognized that the widely used ray theory approach to the acoustic-soil mechanical interactions associated with the remote sensing of sea floor parameters would not yield, in all likelihood, increased insights into the basic processes. While the theory has provided substantial understanding in some acoustic fields of study, a theory which is more sensitive to subbottom parameters is necessary. A field theoretical approach was pursued early in the project because the all-important physical phenomenology can be included in the analysis. The field theoretical approach is often discarded because of mathematical difficulties. However, when we seek sensitive interrelationships of acoustic and physical parameters in a multi-layered environment, we can not oversimplify the analysis. The emphasis during the first two years has been to overcome the mathematical complexities with simple models, which are increased step by step in complexity until they adequately represent the physical world. This general approach has been discussed in detail in proposals[1,5] and more recently in technical theses and papers[6,7,8,9,10,11,12,13,14].

The models, based on the physical configuration shown in Figure 2, have been developed for the full range of equivalent angles of incidence from normal incidence to highly oblique angles.* The results obtained are for water depths of 50 to 600 feet (see Figure 3) and for frequencies (see Figure 3) of 3 to 20 KHz. The results are for the acoustic response created by a steady state point source in a semiinfinite liquid overlaying of visco-elastic halfspace, with n-layers of differing properties. By the end of the second year the following has been accomplished:

1. Formal Solution of an n-layer liquid viscoelastic system has been developed and Green's function formalism for an arbitrary layer expressed. By "formalism" it is implied that at least the integral form of Green's function is determined.

2. One layer Green's function expression has been obtained through computer analysis and by using stationary phase approximations. The results are quasi-ray theoretical and they contain the contributions of shear waves. Ray theory is shown to be a very special case of an idealized theoretical model.

3. Soil mechanical effects such as porosity and liquid content have been introduced and deviations due to these effects have been obtained.

4. It has been demonstrated that secondary effects such as reverberation, bottom roughness, heterogeneity and other perturbations from idealized model can be treated by the field theoretical model. Analysis has commenced on:

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* Angles of incidence by Snell's Law have no meaning in a field theory approach; however, for convenience of discussion, an equivalent angle of incidence is that incidence angle predicted by ray theory for the projector/sea floor hydrophone geometry employed in the field theory analysis.

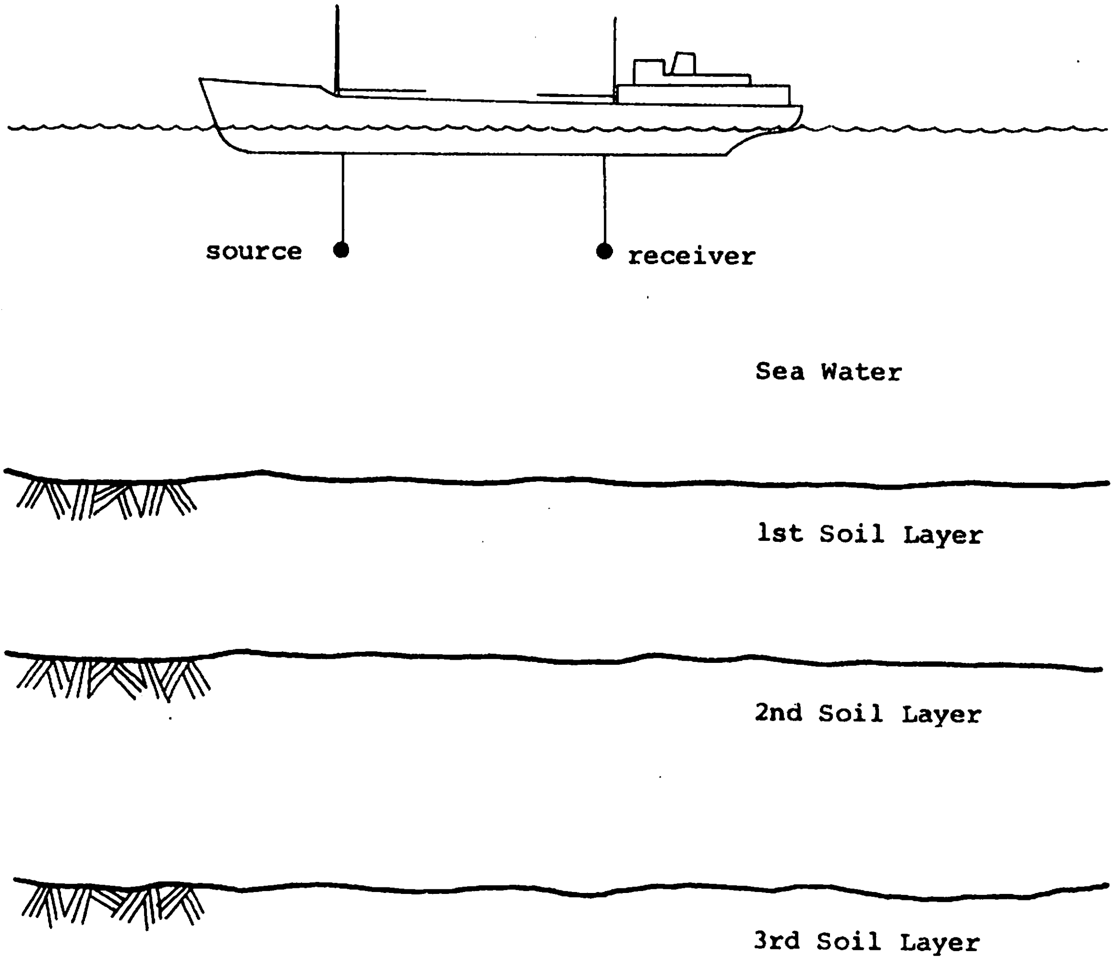

Figure 2

Physical Configuration Used In
Acousto-Soil Mechanical Model Development

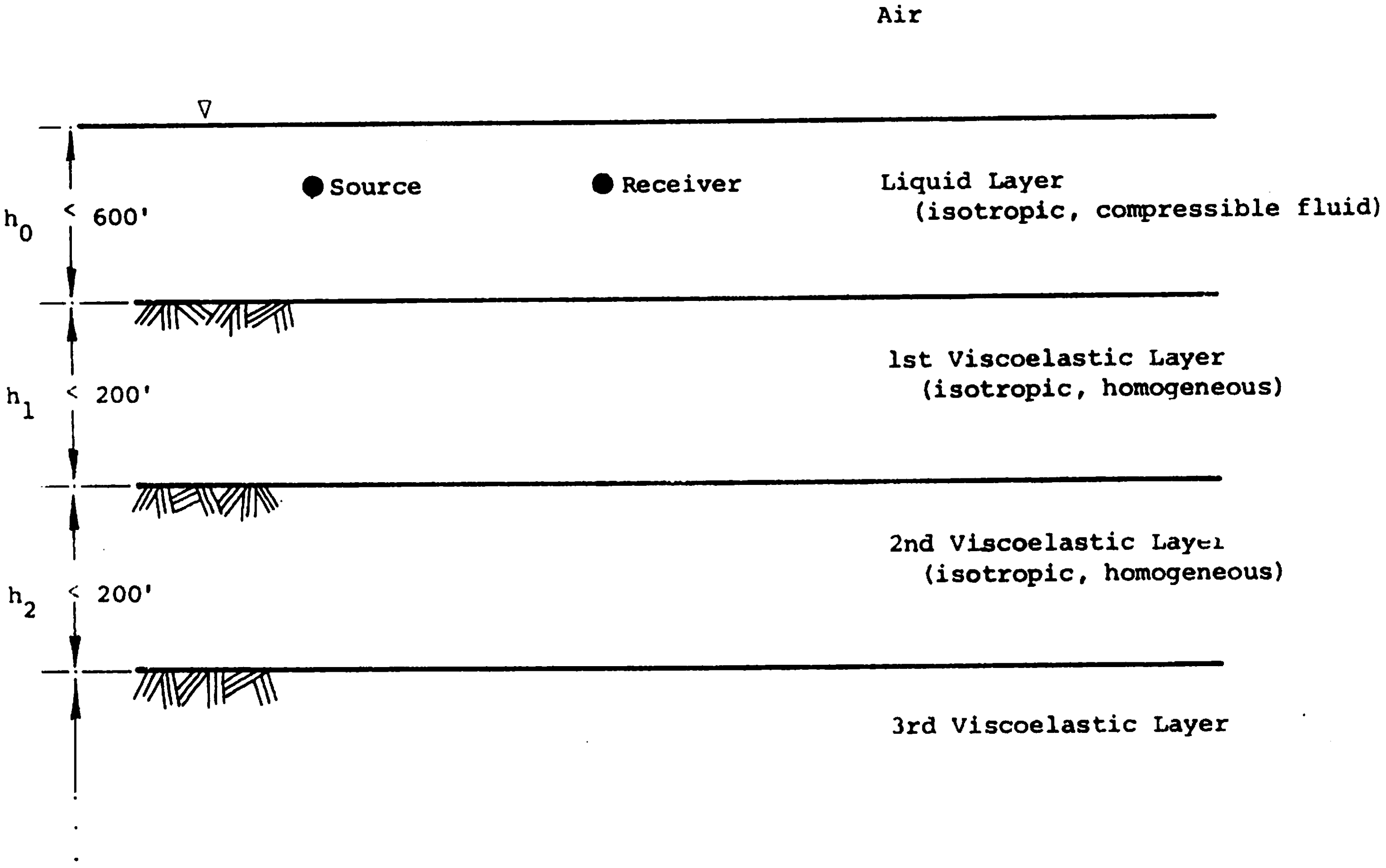

Figure 3

Initial Idealized Multi-Layer

Acousto-Soil Mechanical Model

a) Reverberation created by propagation in an inhomogenous liquid media;

b) Reverberation caused by interface variations such as bottom roughness;

c) Reverberation created by subbottom inhomogeneities;

d) Non-sharp boundary conditions;

e) Non-linear effects, primarily in the subbottom.

The importance of the model development activities can best be understood by a review of two papers in Appendix III (Parts A and B), which expand on the ideas listed above. The reader is also referred to Appendix II, Figure A, to obtain an overview of progress on each part of the model development aspects of this project.

Computer Analysis and Model Corroboration for Theoretical Analysis

Extensive computer studies have been conducted to begin an understanding of the implications of the Green's function formulation of the single layer model (analytical details in Appendix III, Part A). The computer work was designed to:

1) Provide an "exact" solution by numerical techniques to the closed-form integral formulation to the single-layer viscoelastic model, described in Appendix III, Part A and published elsewhere[6,8,14].

2) To compare the "exact" solution with classical ray theory predictions for the same geometries and conditions.

3) To compare the "exact" solution with other methods of solution which might be potentially more efficient in computer time, such as stationary phase approximation.

4) To provide theoretical insight into model behaviour so as to develop predictors and classifiers that would be effective in experimental

and operational systems to locate, identify and classify marine subbottom materials.

Computer programs are operational to accomplish all of the above. The results of these computer analysis have been most promising. An overview of several of the objectives listed above can be seen in Figure 4. The graph depicts the Green's function gain (output acoustic pressure level divided by input acoustic source pressure level) for several conditions (numerical listing below correlates with numbered curves on Figure 4).

1) The model predicted "exact" gain obtained by numerical integration of the integral formulation of the Green's function for a single layered model, using sediment property data from Core # 59-1 obtained by the project team in Narragarsett Bay.

2) The ray theory prediction for the same core as in 1. Note the marked deviation of the two models above an equivalent angle of incidence of 60^o or so.

3) The model prediction using stationary phase approximation for the single layered model and using Core # 59-1 data.

4) The model predicted "exact" gain for a hypothetical sediment having the same impedance as core # 59-1, but 1/1.1 density and 1.1 longitudinal wave velocity.

5) Ray theory prediction from the hypothetical sediment noted in 4.

6) Stationary phase approximation prediction for the hypothetical sediment.

These analysis have helped us quantify from a theoretical viewpoint the correlations between various models. The important point is that substantial difference exists between the various models at higher angles of incidence. This fact, coupled with the predictions for "Hamilton" soils in

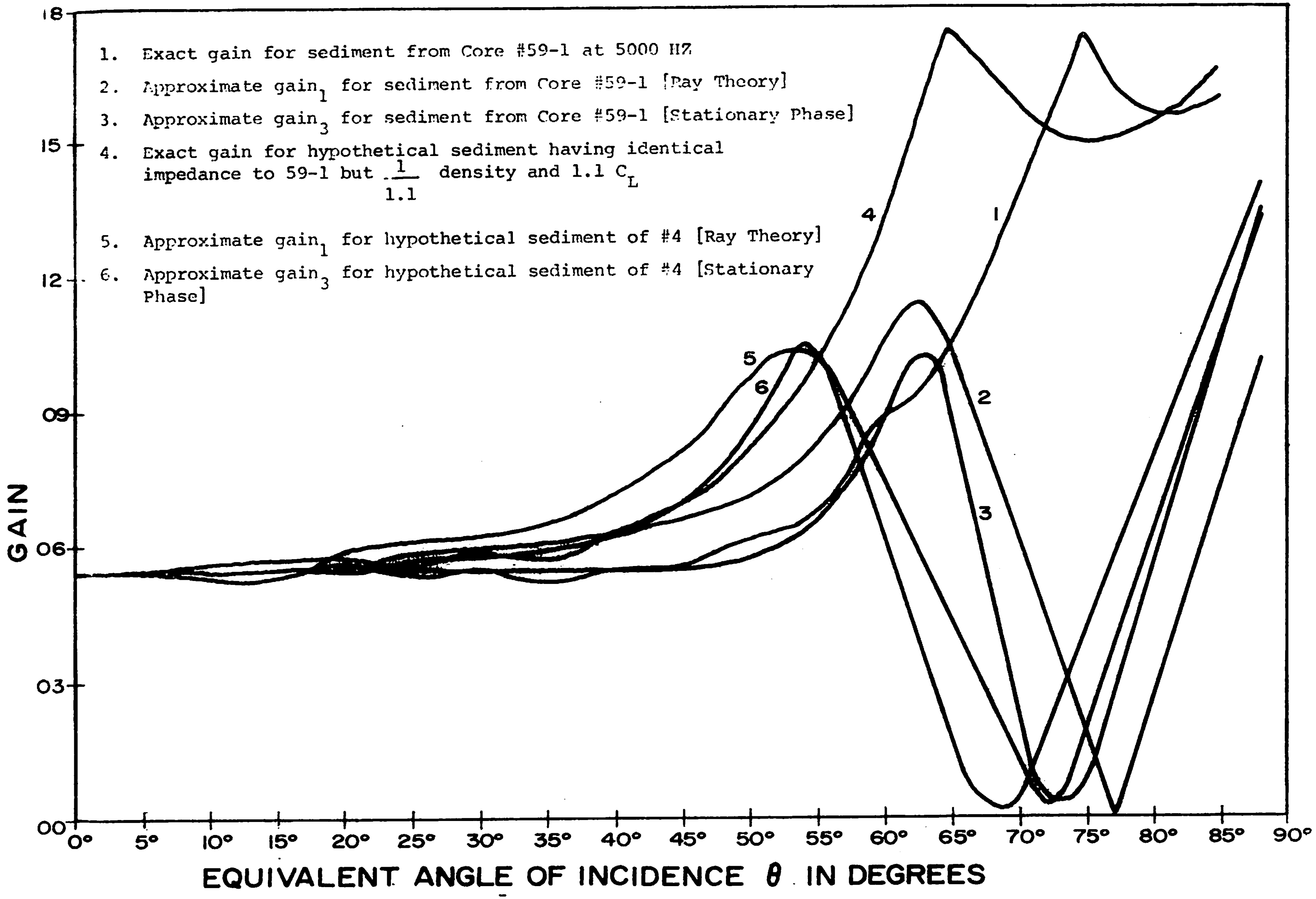

Figure 4

System Gain Versus Equivalent Angle of Incidence for Constant Sediment Impedance and Bounce Distance

Figure 5, suggests the important role oblique profiling techniques have to the classification and identification of submarine soils.

Figure 5 summarizes a computer study which predicted the "gains" for the "exact" single layer model for real oceanic sediments.[16] As can be seen, at higher angles of incidence the gain separation for the various sediment types is sufficient to strongly suggest a methodology for classification of sediments into several distinctive categories. It is evident that sand and gravel is at one end of the gain spectrum, and hence is likely to be identifiable by oblique methods.

These computer studies have been of vital importance in developing useful theoretical approaches to the acoustical classification of sedimentary types, an essential tool to the development of a mineral resource technology. The computer work has resulted in other technical progress, such as a general theory for compensation acoustic transducers, which is a direct product of this research effort.[15]

SOIL MECHANICS AND GEOMORPHOLOGY

Several aspects of soil mechanics and geomorphology have been studied during the past year. A comprehensive effort has been made to integrate into the analytical model development activities the fundamental soil mechanical property descriptors, e.g. as Lamé constants. These efforts can be seen by reviewing the model development section and Appendix III.

The remainder of activity in this area has been related to experimental soils data acquisition. These can be described in two categories.

1. Data related to the classification of marine sediments (classification data).

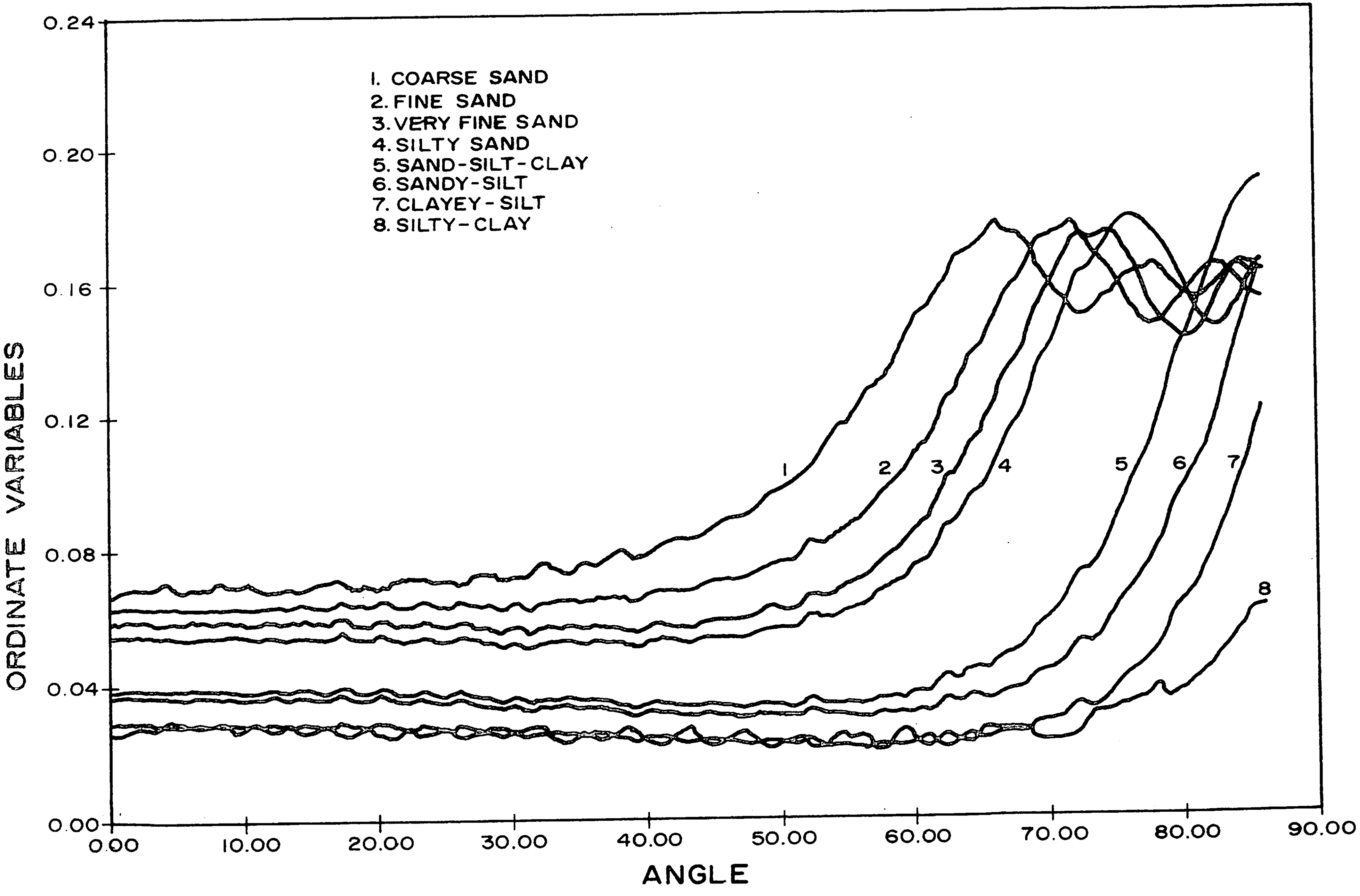

Figure 5

System Gain for Exact Model Versus Equivalent Angle of Incidence
For Typical Oceanic Sediment Types

2. Data related to the identification of marine soils engineering properties (engineering properties data).

Classification Data - During the first year of the project marine core data was obtained by a UNH-developed vibracoring system.[4] Data, both soil mechanical and geomorphological, were obtained from cores taken at acoustically-probed sites.[4] Among the coring areas, two locations were specifically significant in that oblique acoustic experiments were made also:

1. Mackeral Cove: Cores 56 and 59 were taken. Core 56 was not measured for velocities in the lab for the first 3 or 5 feet and was therefore rejected for experimental-theoretical correlation efforts. Core 59 was the most uniform in acoustic reflection as a function of core section depth.
2. Price's Neck: Cores 58 and 60 were taken. Core 58 was second best in acoustic uniformity as a function of core section depth, and core 60 was the least uniform. The uniformity ratios are tabulated below for all the cores considered; cores 58, 59 and 60.
3. The measure of core acoustical uniformity as a function of core section depth was computed as follows: The normal-incidence acoustic reflection coefficient was computed from the soil laboratory data for each 1 foot core section as a function of the depth of that core section. Then the variation of this coefficient as a function of core section depth was tabulated, and is shown below.

The normal-incidence acoustic reflection coefficient is R:

$$R = \frac{Z_{Sed} - Z_{H_2O}}{Z_{Sed} + Z_{H_2O}} \quad \text{where } Z_{Sed} = C_{L_{Sed}} \; \rho_{Wet_{Sed}} \quad \text{and}$$

$$Z_{H_2O} = C_{H_2O} = 1501 \times 1.025$$

$$\rho_{Wet_{Sed}} = \rho_{Dry_{Sed}} (1 - \eta) + 1.025\,\eta \text{ where } \eta = \text{Porosity.}$$

The uniformity ratios tabulated below are defined as:

$PCT(J) = R(J)/R(1)$ for each $J = 1,2,3, \cdots$ where J signifies the core section depth below the bottom in feet.

DEPTH J	PCT58	PCT59	PCT60
1	1.000	1.000	1.000
2	1.0771	1.0275	1.0727
3	1.1730	1.0207	1.1392
4	1.0823	1.0079	1.2357
5	1.0152	0.99002	1.2931
6	0.95337	1.0099	1.2856
7	1.0236	0.87124	1.1630
8	1.0852	1.0130	1.0959
9	1.0640	0.93460	1.0245
10	1.1319	1.2456	1.0875
11	1.2638	0.92906	1.0298
12	1.1676	1.2641	1.0359
13	1.1210	1.2910	0.99520
14	1.0808	1.1957	not taken

During the second year, an improved soil mechanics/geomorphology laboratory was established to enable the project team to analyze a broader range of sediment properties and characteristics. Methods, with associated apparatus, were established to do most of the standard soils analyses, i.e. grain size, distributions, porosity, etc.

Based upon the extensive experience gained during the first year of field operations, a Model II of the vibracoring system was designed and placed into operation. The Model II corer was used to acquire cores obtained during the second year. The essential differences in the newer coring unit are design details to extend the length of cores obtained and to ease operations in granular materials. Cores up to 25 feet in length were obtained in sands and fine gravels. The data obtained from these cores were analyzed in a manner similar to the results reported in the first year.[4,5]

Essential to the classification problem is obtaining longitudinal and transverse (i.e. compressional and shear) wave velocities. During the past year prototype instruments were designed and constructed to measure both of these soil velocity parameters. Measurements made with the laboratory prototype correlate well with published data in the literature. While they have been used on core samples only, the principles employed in the laboratory models could be used in in-situ systems. The shear wave velocimeter has important implications to the present research activity and should be more fully developed.

Engineering Properties Data - One of the early objectives of our project was to develop the capability of evaluating bearing capacity of ocean bottom soils. To aid in the correlation of acoustics and soil properties, and also to serve as a necessary component of a soil property evaluation system, we are planning to develop an in-situ physical sampling system.

During the second year, this task was only in the planning stage. But as an outgrowth of these plans, a student engineering design project team undertook the design and construction of an underwater dynamic cone penetrometer. The cone penetrometer is a device used both on land and in the sea, which gives an indication of soil engineering properties such as internal friction angle, relative density, bearing strength. In a dynamic type penetrometer the core is driven into the soil by repeated impulses at a given energy level. Our prototype penetrometer uses a 140-pound weight "dropped" through a distance of 30 inches, which is the standard "blow" count system used in terrestrial penetrometers.

A student project team designed and constructed a prototype penetrometer for use in shallow water (50 feet), which has not been fully tested in-situ. When operational, it will have the capability of driving a cone 10 feet into ocean bottom soils. Divers will level the device and extract the cone with a winch. The prototype stands 16 feet high on three supports. The device is powered by storage batteries.

The prototype penetrometer will be used to study the correlation between soil properties, both physical and acoustic, and penetrometer data. A theoretical analysis of the cone-soil interaction is now underway which we hope will help to identify the significant parameters essential to experimentally evaluating bearing strengths. We also plan to develop further the prototype device so that it can be used to implant other in-situ measuring instruments.

Signal Process of Experimental Acoustic Data

Extensive acoustic and physical data have been acquired as a part of this project. The initial phases of these experimental data acquisition cruises were reported in the First Annual Report[4], and the details concerning data gathered during the second year are reported elsewhere[5,17, 20-26], but can be summarized below.

1. An extensive data bank of acoustic signatures for a variety of known sedimentary types has been obtained employing a range of source center frequencies from 3 to 16 KHz. Acoustic sampling were matched with core data to search for acoustical indicators of soil properties and characteristics.

2. The acoustic data was corrected for calibration and geometry factors and converted from analog to digital form for signal processing at UNH and Raytheon in computer-compatible formats.

3. Data processing and analytical formalisms were developed for examining acoustic signatures in the data bank, using both the field theoretic and a plane wave computer model of the soils, such as envelope detection, ensemble averaging and similar statistical techniques.

4. Analysis and experiments on spatial variability created by movement of acoustic projectors and hydrophores was conducted.

5. Envelop detection techniques were developed and made operational which employ digital filtering techniques, including FFT's, to obtain the required Hilbert Transforms.

6. Power spectral analysis program to analyze acoustic data are operational. Several FFT approaches and window types and sizes were investigated to obtain the most effective algorithm.

7. Computer programs were written and tested to find system gains in the experimental program which correlate with the theoretical models. Efforts are still underway to optimize these analyses of data subject to spatial and temporal variabilities.

8. An analysis of second year data has yielded three distinct conclusions regarding sources of variability in quantitative measurements of bottom-reflected sound. First, significant reduction in the amount of scatter exhibited by acoustic data can be effected by using acoustic measuring systems possessing increased spatial stability. Such a system should include an automatic acoustic path length compensation technique to correct for residual spatial variabilities caused by movements in the monitoring geometrics. Second, a further increase in data consistency can be achieved through the incorporation of narrow-band analysis techniques

as opposed to a total energy analysis approach. Third, it is concluded that a significant increase in the confidence of these measurements can be attained by calculation of acoustic indices based upon ensemble averaging of an extended time series of pulse return data.

9. Data analysis has shown a substantial impact of observed data variability on sediment identification and classification models. It now appears that even under the most optimum of experimental conditions, all principle acoustic index values will contain some level of variability; e.g. a 0.85 dB standard deviation was measured for a fully stabilized, path length corrected, narrow-band bottom loss measurements. Prediction models, either analytically derived or empirically developed, which require these acoustic indices for sediment type, class, or physical property identification will have to account for this naturally occurring variability of the acoustic data. These general conclusions were derived from our experimental acoustical data collection activities. The first year's data were subjected to substantial analysis, resulting in a series of observations that guided the data collection in the second year. These analyses suggest that:

1. Spatial variability of the sediments in the test areas (Narragansett Bay) is very high, contributes to high scatter in the resulting acoustic measurements.

2. Ship motion contributes significantly to the variability in acoustic data, not only in the timing meter relationship but to sensor beam pattern effects resulting from yaw and pitch motions, and to background noise, all of which increase the spatial variability of the acoustic signatures from marine sediments.

3. Normal incidence measurements essentially repeated published reflection coefficients data without enhancing our understanding and hence

should be augmented with oblique techniques.

Behind our data collection efforts was a general policy to examine a few carefully chosen sites in substantial detail. Much of the work reported in the literature provides statistical averages over widely scattered sites. Our intent to generate a predictive tool requires precise examination, physically and acoustically of highly specific sites.

The second year's data collection included the following factors:

1) Additional coring to establish the horizontal variability in the sediments;

2) A stabilized bottom-mounted array to remove ship motion;

3) A series of experiments that provide oblique measurements in addition to the normal array configuration;

4) A series of tests with new sound sources, including a parametric (finite amplitude) source providing a very narrow beam, a boomer, and a chirp transmit format with a correlation receiver;

5) Data taken at a series of discrete frequencies;

6) Optimized sensor geometrics to avoid data interference from multipath echoes;

7) Non-linear amplification to permit coping with the extended signal dynamic range;

8) Collection of sufficient data samples from each basic configuration to permit ensemble averaging;

9) All data was accumulated on analog magnetic tape.

Data were accumulated from six sites chosen from the first year's study to possess distinct combination of sediments. These included:

1. Mackeral Cove
2. Price's Neck
3. Sakonnett River

4. West Passage
5. Scarborough Beach
6. Point Judith

Eighty-five test configurations were explored. A total of 22 days of at-sea data collection were accomplished with literally several million data points being collected.

The Development of an Exploration Systems Technology

A primary objective of Raytheon's participation in this project is the ultimate development of a technology, and, indeed, an operating system for remote sediment classification. The state-of-the-art at the time of program inception was obviously inadequate for system design. The work of the first two years in developing a theoretical model and a satisfactory data base are necessary prerequisites for such a design.

We can, today, measure fairly reliably the quantitative vertical reflectivity coefficient of first, second and possibly additional layers and establish the attenuation coefficient of the intervening sediments which is related to porosity of the soils.

System development is proceeding along the following steps:

1) To achieve a higher parametric sensitivity through techniques such as oblique analysis;

2) To reduce data scatter through motion stabilization;

3) To obtain effective ensemble averaging;

4) To obtain rapid inexpensive frequency domain analysis;

5) To expand the number of reliable parameters, to permit sediment characterization through a multi-element matrix description.

Environment Ecological Impact of Nearshore Mining Of Sand and Gravel

Introduction

Until recently little attention has been directed to the ecological effects of dredging and mining on marine communities. Due to the scarcity and increasing cost of terrestrial materials, increased pressure is being directed to state and federal government agencies to license nearshore mining of sand and gravel. Marine mining in significant volumes is already taking place around the world; British firms have been dredging sand and gravel commercially for years (Hess, 1971)[27]. Edmiston (1971)[28] cited experts who predict that "offshore mineral mining will grow at such a fantastic pace that by the year 2000 it will match the activity and money then being spent by offshore oil." The magnitude of the operations envisaged makes it imperative that comprehensive environmental impact studies be carried out to provide government agencies and industries with knowledge to intelligently exploit subsea mineral resources with a minimum of disruption of the marine environment (Cronin et al, 1971[29] and Hillman, 1971)[30].

The exploitation of marine sand and gravel deposits has several ecological implications, the more obvious being the direct destruction of habitats (benthic and pelagic), and the alteration of "down-current" habitats from increased turbidity and/or excessive siltation (Goodier and Sochle, 1971)[31]. The secondary effects of such mining (i.e. siltation and increased turbidity) may be more important, at least during the dredging operation, than the localized destruction caused by substrate and organism removal. Suspended sediments can modify the quality of light and decrease the quantity of light penetration to different depths. Any major change in the quality and/or quantity of light will be reflected in the composition of of photosynthetic organisms and subsequently in the benthic and pelagic fauna dependent upon them for food.

The organisms which compose the spring diatom bloom spend a major portion of the year on the surface of the bottom muds. The sediments, which arise from the dredging, cover the bottom mud, thereby isolating the population of algae which produce the spring blooms. The increased sediment load also changes the nutrient composition of the water through absorption and diffusion. The species composition of the algae may be influenced by nutrients and light composition.

Silt deposits can smother benthic organisms and inhibit recruitment of their juvenile stages (Grigg and Kiwala, 1970)[32]. Both benthic and pelagic filter feeding animals, may find extreme difficulty in maintaining metabolic efficiency under conditions of high turbidity (Davis, 1960[33] and Loosanoff, 1961)[34]. As a result of a decreased feeding efficiency, there could well be decreases in growth rate, condition index, sexual maturation and number of viable gametes. One might expect the following types of changes to occur: (1) a decrease in the number of taxa (Grigg and Kiwala, 1970)[32]; (2) a decrease in biomass (g/M^2) and/or primary productivity (Phinney, 1959[35] and Taylor et al, 1968)[36]; (3) modifications of seasonal and spatial successions of organisms (Reish, 1961)[37]; (4) an emergence of photosynthetic organisms (Cronin et al,[29] 1971 and Taylor et al, 1968)[36].

The purpose of the Ecology Section of the University of New Hampshire-Raytheon Company Sea Grant Program is to study the environmental effects of sand and gravel mining on pelagic and benthic communities. The program, as originally proposed, was to be an ecological impact study of a commercial dredging operation in Massachusetts Bay in order to provide baseline information on the effects of such operations on marine communities, if any, and to work with industry and state and federal agencies to develop criteria which would minimize potential detrimental effects. The study was to be done in Massachusetts Bay due to the strong interest on the part of the state government in Massachusetts, particularly the Division of Mineral Resources, to have the necessary ecological impact information to intelligently grant leases within the state's territorial waters. The study was to begin in June, 1971 with the establishment of permanent stations, which would provide baseline data, about a year before the dredge operation took place. The study was then to continue for the duration of the dredge operation, and for a year to two years after the end of the operation. During the follow-up studies, the effects of the dredging on marine communities would be outlined and the criteria for minimizing potential harmful effects proposed.

In order to determine the environmental effects of marine mining, on pelagic and benthic communities, five inter-dependent projects were proposed. The Environmental Systems Center of Raytheon Company was to study Zooplankton and Finfish Communities while the Ecology group at the University of New Hampshire was to conduct studies of Phytoplankton and Benthic Communities - both flora and fauna. The research teams were to share the responsibility of collecting physical and chemical data to interrelate their biological sampling data. The Zooplankton and Finfish studies were not initiated in 1971-72 because of funding problems. A second handicap to the initial program was the difficulty of finding a dredge operation; without a dredge operation, it was impossible to establish baseline study sites.

In order to refine sampling and laboratory techniques and to develop a familiarity with the fauna and flora of Boston Bay, the University of New Hampshire's research teams established a series of stations and began sampling these on a monthly basis during the summer of 1971. Two of the stations were near the large sand spit off Great Brewster Island, where dredging for sand had already occurred and might conceivably be reestablished. The third site was well north of this area and it could have served as a control site should a dredging operation be instituted at the Great Brewster Sand Spit. Monthly sampling at these stations continued through the remainder of the first year. In order to provide a broader spectrum of information on the plankton communities, four other plankton stations were established northward to Portsmouth Harbor, New Hampshire. In the following sections, the techniques of the individual projects and the information collected will be summarized. The results of these studies are being tabulated. Specific technical reports will be submitted in the near future as well as reprints of papers submitted for publication.

Site Descriptions and Techniques

A. Description of Stations

Seven stations encompassing a distance of 60 miles are included in this study: Rye, Merrimack, Annisquam, Bakers Island, Flip Rock, Pope Rock and the Barge. Benthic studies were carried out at Flip Rock, Pope Rock and the Barge station, phytoplankton populations were examined at all but the Barge station. The first three stations (Rye, Merrimack and Annisquam) lie north of Cape Ann (70° 35' W, 42° 37' N); the other four are located in Massachusetts Bay.

Site 1. RYE. The most northerly station of the transect (43° 0' 33" N, 70° 43' 0" W) lies 2 km off Rye, New Hampshire in 20 meters of water. The site is 3 km from the mouth of the Piscataqua River and the Great Bay Estuary System. The site is exposed to the open sea from the north, east, and south.

Site 2. MERRIMACK. The Merrimack Station (43° 0' 30" N, 70° 43' 0" W) is 12 km south of Rye, 1.5 km off the mouth of the Merrimack River and in 12 meters of water. Runoff from the Merrimack River is conspicuous; its flow often dominates the physical characteristics of the site. The station is exposed to the open sea from the north and east, and partially exposed to the south-southeast where Cape Ann forms a barrier to some water flow.

Site 3. ANNISQUAM. The Annisquam station (42° 40' 0" N, 70° 40' 0" W) is 9.5 km south of the Merrimack station, 1 mile north of the Annisquam Canal and in 12 meters of water. The site is well protected, being only partially exposed to the north-northeast and enclosed by Cape Ann on the other sides. The influence of the Merrimack River is often noted in the physical characteristics of the water mass.

Site 4. BAKERS ISLAND. The Bakers Island (42° 32' 0" N, 70° 47' 0" W) station is 15 km northeast of Boston Harbor, south of Cape Ann, 4 km off Salem and in water 10 meters deep. The site is exposed to the south and east and protected in the north and west.

Site 5. FLIP ROCK. The Flip Rock station (70° 55' 32" W, 42° 24' 14" N) lies in the deepest water (22 meters) of the three Massachusetts Bay stations; it is also the most exposed site. Flip Rock consists of a group of large subtidal rock and ledges located two miles offshore. The surrounding area is characterized by a flat, muddy-sand bottom. The top of the rock is always submerged by five meters or more of water.

Site 6. POPE ROCK. (70° 53' 35" W, 42° 20' 43" N) is a rock area on the open coast. It is subject to moderate wave action. The substrate at Pope Rock consits of a massive rock ledge and large boulders; unlike Flip Rock and the Barge, which are always submerged, the substrate at Pope Rock extends above the high tide mark and to a depth of 12 meters.

The station is exposed from the Northwest or Northeast and is protected on all other sides. The tidal amplitude at Pope Rock is approximately 3 meters.

Site 7. BARGE. The Barge (70° 54' 00" W, 42° 20' 13" N) is a large (65m x 20m x 5m) sunken metal boat lying in 8 meters of water on a muddy-sand bottom off Great Brewster Island. The top of the barge is covered with about one meter of water at low tide. The barge is subjected to tidal currents of over two knots and it is protected from extreme wind and wave action, except when the wind is out of the Northwest.

B. Sampline Techniques

1. Phytoplankton

Six stations were established in order to compare and contrast their phytoplankton populations.

Monthly samples have been taken from August to the present on board the R. V. Jere A. Chase, a 46' research vessel operated by the University of New Hampshire. A series of physical and biological samples were also collected at each station.

Light measurements were made at 1 meter intervals from the surface to the compensation depth (1% of surface light). Salinity and temperature measurements were also made at 1 meter depths to 8-14 meters. Oxygen concentration was measured from surface water samples at each station. Six 300 ml aliquots were siphoned off from each water sample; two aliquots were fixed immediately and stored for laboratory titration. Four other aliquots were placed in two light and two dark B.O.D. bottles; they were incubated four hours in a shipboard incubator with constant water temperature and light intensity. Each set of incubated samples was fixed after four hours, and titrated after return to the lab.

Two-liter water samples were taken at the surface, 5 meters, and 1.5 meters off the bottom at each station. A 285 ml aliquot of each two-liter sample was immediately preserved aboard ship and stored for laboratory analysis. The preserved samples were used to determine population densities, total particle volume, and number of cells within each size class. Characteristic members of each species were photographed as a permanent record of the collection and as an aid in identifying some species. At times, species identification was hampered due to the small size of individual cells. In this case the volume was concentrated in acetyline tubes, the supernant drawn off, and the species preserved for electron microscopy. A second aliquot of the two-liter sample was withdrawn and filtered through a millipore filtering apparatus. The filters were homogenized with five ml of 90% acetone and placed in a darkened refrigerator for periods of 24 hours to two weeks. After 30 minutes of centrifugation the optimal density of the samples were evaluated with a Beckman UV-VIS spectrophotometer. Chlorophyll A,B, carotene, and phaeophytin concentrations were calculated.

A plankton net was towed for five minutes (at a speed of one knot) at each station. The sample was used as a qualitative sample for species identification; it was preserved with formalin for a permanent record.

2. Benthic Communities

a. General

Monthly samples of the benthic plant and animals have been taken since August, 1971 at stations 5, 6 and 7. Samples were collected from the R/V Jere A Chase using SCUBA techniques on the day following the phytoplankton sampling so that the hydrographic data could be used for both projects. Samples of the benthic fauna and flora are collected at the following depths below mean low water; 5 and 15 meters at site 5; 3, 7 and 10 meters at site 6; 1 and 3 meters at site 7. The depths were selected after determining substrate availability at the three stations. At each depth and station a series of four ¼m^2 quadrats are denuded from the substrate, and placed into fine mesh nylon bags held open by a square wooden frame. A photographic record of the sample sites is being made. The samples are subsequently frozen prior to sorting in the laboratory. Upon returning to the laboratory the algae are separated from the animal forms. The plants and animals are analyzed separately.

b. Flora

A ¼m^2 quadrat is now being employed for quantitative sampling. In the laboratory the samples are separated according to species and the total damp dried weight of each organism is recorded. In addition the length and weight of each kelp plant (Alaria, Agarum and Laminaria spp) are recorded - the latter plants are the largest and most productive plants at the stations. An attempt has also been made to evaluate the vertical distribution of the seaweeds at each station. Herbarium voucher specimens of each species are prepared (monthly) and deposited in the Algal Herbarium of the University of New Hampshire as a permanent documentation of the flora.

c. Fauna

Collection of benthic invertebrates were originally made using a one-sixteenth square meter quadrat; this has now been modified to a ¼m^2 quadrat for a joint plant-animal sampling program. A qualitative sample is also taken at each sampling station. A preliminary species list is prepared on the vessel and observations are recorded on the general condition of the community. In the laboratory, the total wet weight of the sample is taken. The sample is then subjected to a primary sorting into major groups. A wet weight is then taken of each grouping. The subsamples are separated into more definite taxa. A reference collection of invertebrates is being established at the Jackson Estuarine Laboratory as a permanent documentation of the benthic fauna.

Results

A. General

Monthly sampling of the stations described above began in August, 1971 and is continuing at present. However, due to the volume of material collected in the field program and the limited number of personnel involved, there has been a lag in the laboratory analysis phase of the program. The completion of laboratory analyses and the summarizing of results are proceeding at such a rate that completed technical reports of this initial program of environmental assessment will be available for all three ecology subprojects before the end of the third year of the program. Copies of these reports as well as reprints of abstracts and papers resulting from these studies will be submitted to the Sea Grant Office. The types of information that are now being summarized in the three projects are described below.

B. Phytoplankton

The hydrographic data includes tables and graphs of oxygen concentration, salinity, temperature and light penetration by station and by month. Biological data on phytoplankton includes measurement of productivity and biomass as determined by cholorphyill measurements and coulter counts. Species lists and cell numbers are being compiled, and they will provide information on species composition and population fluctuations over a year.

The populations of phytoplankton obtained at the six stations were different from one another both in species composition and abundance. Even the Pope Rock - Flip Rock stations, although only eight miles apart, show significant qualitative and quantitative differences. Whether these variations are temporal or spatial can only be ascertained by the inclusion of more stations and more frequent sampling at each site.

C. Benthic Communities

The results of the studies on the benthic communities at the three stations described previously will include characterization of the stations and the sites sampled by depth. The descriptions of the communities will include species lists with information on biomass, species numbers, diversity indices and population fluctuations. Particular emphasis is being paid to natural fluctuations of populations, in order to better interpret potential dredge effects.

The reference materials (both plant and animals) will be made available to interested investigators, and they will ultimately be housed at an appropriate national archive. All of the biological data will be analyzed by suitable statistical programs in order to determine any possible correlations with the hydrographic data.

D. Observations

Although the final results have not been summarized, several conclusions concerning these studies are obvious. While monthly sampling appears to be quite adequate for benthic studies, phytoplankton populations turn over so quickly that monthly sampling is inadequate to obtain a clear picture of phytoplankton populations. Therefore, beginning in the summer of 1972 bi-weekly sampling of phytoplankton in Massachusetts Bay is taking place, and it will continue for the duration of the program, particularly in the spring, summer and fall when phytoplankton activity is at a high level.

Funding problems severely limited the ecology section during this initial year of the Ecology Program, for the manpower was inadequate. The personnel was adequate for field sampling, but not adequate for analyzing the monthly samples. To illustrate this point, a skilled technician working full time can presort and final sort a sample from a ¼m^2 quadrat in about 2½ days. Approximately twenty-five to twenty-eight such samples were collected each month from the three stations and the personnel in the benthic fauna study consisted of a half-time graduate student during the school year and the principle investigator working part time on the project. Similar volumes of samples combined with similar manpower limitations affected the other two programs. In any such study involving periodic field sampling and laboratory analyses, the manpower requirements will be a critical limiting factor for the program.

Development of the NOMES Program

As originally conceived, the central thrust of this Sea Grant Project was aimed at the development of a soils assessment technology, central to the basic skills of the involved university and industry and, indeed, responsive to their prime motivations. The questions of the societal impact of using the sea floor as described in the project's five-year plan necessarily assumed secondary attention. These lower priority questions, however, in the broader context are the far more important ones, and certainly required attention beyond that allotted in the available budget.

Based, however, on the ecological studies during this 1971-1972 year, and on the joint interest and awareness of the Marine Minerals Technology Center of NOAA, a much broader examination of the environmental impact of offshore mining became crucial. In January 1972 members of the Marine Minerals Technology Center at Tiburon, California of the Environmental Research Laboratories in NOAA visited the University of New Hampshire.

They proposed an expansion of the ecology segment of the UNH-Raytheon Sea Grant Program to form a multi-institutional and multi-disciplinary study of a simulated dredging operation to take place in Massachusetts Bay some time in the spring of 1974. Since January, the program has taken shape to become the NOAA sponsored New England Offshore Mining Environmental Study (NOMES). The three ecology projects at the University of New Hampshire have expanded in scope and size and two new projects have been added under funding from the Marine Minerals Technology Center. Concurrent with the expansion of the scope of the ecology study there has been an increase in funding and there now appears to be adequate support for personnel. A detailed overview of NOMES is contained in Appendix III, Part C.

III. MANAGEMENT AND INTER-INSTITUTIONAL ASPECTS OF THE PROJECT

General Overview

This Sea Grant Project is unique since it involves partnership between the University of New Hampshire and the Raytheon Company's Submarine Signal Division. The project differs from most in that it possesses a shared leadership in a fully integrated complex research effort. Unlike the more common client-consultant relationship noted elsewhere in university-industry teams, we are attempting to make scientific progress in a most difficult technical area, by building collaboratively on the very different skills in two quite disparate organizations.

The University and an industry live with widely different objectives, organizations, rewards and measures. The academic and the industrial technologist move in drastically different and sometimes antagonistic worlds. Yet this joint project purports to fully integrate these disparate functions with a shared direction to achieve a common purpose. At the end of our second year, after all the initiations, stresses, arguments, disappointments and successes, we cannot state equivocally that such a partnership is practical. Yet at this juncture we are still operating jointly with shared objectives and common hopes, and are looking ahead to even more rewarding accomplishments. In the overview, an observer would have to admit that progress is being made.

The key to success in any such collaborations between opposites lies directly on the personnel. To achieve both partners must be characterized by ingenuity, awareness, an ability to listen, and a willingness to stand firm one time and bend another. Above all each must possess a deep and honest commitment to make it work, and work together. Our successes and our failures, such as they have been, are directly traceable to our ability to lead. In one sense, our technical achievements would have been far greater if the problems of communications were not so overwhelming. Undeniably, through, there would have been far less progress if we had worked separately. Collaboration, at this juncture, appears to be a difficult, but very promising path to achievement.

The project has had the benefit of counsel from colleagues in the UNH Business School, which has enabled the team to gain operational insight into effective organizational patterns. During the third year, some of these understandings and inter-institutional organizational patterns will be published.

Impact of the Project on the Raytheon Company

At the inception of this project, the management of Raytheon contributed funds and talent in the anticipation that significant values would be returned to the company over the ensuing years. While maintining a long-term view, management has not lost sight of its obligation to achieve a return on its investment.

Significant benefits have accrued to the company which have resulted from participation in the program. Technical skills have developed, and a new business start, called Marine Surveys, has evolved aimed at applying the values of the project to the civil engineering uses of the ocean. This Sea Grant Project has contributed significantly to Raytheon's business which would not otherwise have been achieved.

While the Marine Survey development was underway, Raytheon was also developing a parallel Environmental Survey activity, offering assessments of the water column. Coincident with the development of the NOMES study, the Marine Survey and the Environmental Survey functions were merged in Raytheon thus paralleling in the company the scientific and organizational growth of this entire program.

More important than sales dollars has been the stimulation, the development of awareness, the growth of personnel and the ability to serve that has evolved from the project. The company, of course, has not received a full monetary return for its matching funds in the first two years. Yet, it has good reason to consider its investment a sound one.

Impact of the Project on the University

The impact of the UNH-Raytheon project on educational and research goals of the University can be best summarized categorically as:

1. Development in new course and new research areas inspired by the project. We have developed so far "Theoretical Mechanics," "Non-Linear Mechanics" and are preparing for "Optical Oceanography" in the next semester.

2. Master and Ph.D. thesis have been written in the areas of research and development associated with the UNH-Raytheon Project as listed below:

a) Magnuson, Allen, Sound Propagation in a Liquid Overlying a Viscoelastic Halfspace, Ph. D. Thesis, September 1972.

b) Grochman, Craig F., Effects of Liquid Saturated Porosities on Sound Transmission in an Ocean Subbottom, M.S. Thesis, June 1972.

c) Demos, S., Acoustic Response of a Viscoelastic Semi-Infinite Medium With a Covering Liquid Layer, M.S. Thesis, June 1972.

d) Stewart, Gary K., Sound Transmission in Liquid Viscoelastic Multilayer Media, M.S. Thesis, June 1972.

e) Vogelsong, R., Scattering of Waves From Spherical Inclusions, M.S. Thesis, June 1972.

f) Cepkauskas, M., Propagation of a Rectangular Pulse Through a Randomly Inhomogeneous Media, M.S. Thesis, June 1973 (in preparation).

g) Van Der Beken, S. J., Sound Radiation From an Elastic Rod Imbedded in an Elastic Medium, M.S. Thesis, February 1973 (in preparation).

h) Katsekas, J., The Normal Incidence Acoustic Response for a Liquid Overlying a Viscoelastic Halfspace, M.S. Thesis, February 1973 (in preparation).

i) Vogel, P. M., Volume Reverberation in a Viscoelastic Solid, M.S. Thesis, June 1973 (in preparation).

In the second year we were able to coordinate and identify our educational activities which ocean and ocean-type problems. This not only prepared us to deal with ocean problems when needed, but immensely helped to understand modern social challenges in engineering such as ecology, environment, etc.

In addition to these vital academic achievements, the colleague working relationship with a major industry has stimulated an increased awareness of the industrial mileau. This awareness has broadened the horizons of our students and faculty. It is our firm belief that this industrial/university inter-action is an important component to the educational process.

IV. PERSPECTIVES FOR THE THIRD YEAR

This section is included so that the reader can obtain an overview for the future activities of this project, both in terms of the technical efforts and interaction with the NOMES project.

Third-Year Objectives for The Sea Grant Project

The third year proposal[17], already submitted to NOAA - Sea Grant, can be summarized as follows: The detailed technical discussion focuses on:

1. Continued model development with emphasis on the N-layered sediment;
2. Development of the constitutive equations for marine sediments;
3. Initial development of instruments for soil mechanics data collection to create a data base to study engineering properties of soils;
4. Computer analysis of model, to permit model refinement and correlation with experimental data;
5. Signal processing, and the development of new computer subroutines.
6. Design of a data collection system providing the classification parameters;
7. Ecological evaluation of near-shore mining.

The third-year program of research is striving to achieve the following results:

1. To create a mathematical base that permits us to model a multilayered sediment.
2. To establish a computer representation that enables us to exercise and test this model.
3. To validate the single-layer and N-layer models with experimental data collected this past year.
4. To establish a practical system design concept that incorporates the teachings of the theoretical and experimental studies, and which copes with the real world problems of data collection and analysis.
5. To continue to process field data to refine our assessments of key predictive parameters, to establish improved analysis of the amount and cause of data scatter, and to extend our correlations of acoustic and core data to refine our analysis of inter-relationships.
6. To initiate the soil mechanics studies of bottom soils, to build both a theoretical and practical understanding of sediment parameters, and to permit relating acoustics to load-bearing predictions. This includes development of the constitutive equations as well as the design of certain instruments for parameter measurement and the collection of related data.

NOMES Project Objectives

The New England Offshore Mining Environmental Study (NOMES) is an experiment designed to monitor the ocean environment - before, during and after dredging for commercial grade sand and gravel - to evaluate the direct and indirect ecological effects of offshore mining. The major scientific objective of the experiment is to understand the effect sand and gravel dredging has one the marine ecosystem; thus, enabling us to predict the potential impact of marine mining operations. The experiment is designed to provide a scientific basis for establishing realistic environmental safeguards over future mining operations.

The NOMES Project is a multi-institutional effort, coordinated by NOAA Environmental Research Laboratories, but involving substantial contributions from the UNH-Raytheon Sea Grant Project, the MIT Sea Grant Project, and the technical/professional contributions from other agencies within the Federal Government and within the state of Massachusetts.

The experiment will take place in Massachusetts Bay and will require approximately four and a half years to complete. The project is divided into four phases:

(1972 - 1974) I. Pre-dredging environmental baseline;
(1974) II. Dredging and Monitoring Phase;
(1974 - 1975) III. Post-dredging monitoring and impact study;
(1975 - on) IV. Preparation of guidelines for regulatory agencies.

The project outline, with more details, is contained in Appendix III, Part C.

V. ACCOMPLISHMENTS AND SUMMARY ACTIVITIES

The second year of this Sea Grant Project can be broadly characterized by activities in two general areas.

1. The development of the basic science and technology for the identification and classification of marine soil mechanical properties by a combination of remote acoustic surveys and the physical testing of marine soils, and;

2. The initiation of an environmental/ecological impact study associated with in-situ conditions surrounding actual recovery of sand and gravel deposits.

Within this broad framework we summarize the highlights of project activities and accomplishments within specific technical task activities. More details are given, however, in the main body of this report.

Acousto-Soil Mechanical Model Development

By the end of the second year the theoretical efforts of the project team to model the interaction between acoustic energy and the ocean subbottom has accomplished the following:

1. A formal solution for a model of a multiple-layered ocean bottom using a liquid-viscoelastic approach has been developed. The model considers as primary effects the layering of different subbottom materials, each with differing acoustical and soil mechanical properties.

2. A single layer (bottom deposits whose depth is sufficiently large that no acoustic energy is returned from the second layer) has been analyzed by closed form analyses techniques and by computer approximations to the Green's function formulism. The model indicates substantial gain

separation (input-output response and difference) for oblique angles of incident geometries. The theoretical results suggest a mthod for marine-soil classification.

3. Soil mechanical effects such as porosity and liquid content have been introduced and deviations due to these effects have been obtained.

4. It is demonstrated that secondary effects such as reverberation, bottom roughness, heterogeneity and other perturbations from an idealized model can be treated by the field theoretical model. Analysis has commenced on:

a) Reverberation created by propagation in an inhomogenous liquid media;

b) Reverberation caused by interfacial variations such as bottom roughness;

c) Reverberation created by subbottom inhomogeneities;

d) Non-sharp boundary conditions;

e) Non-linear effects, primarily in the subbottom.

Computer Analysis and Model Corroboration

Our computer studies aid us in determining the gain for the "exact" single layer model for real oceanic sediments. At higher angles of incidence, the gain separation for the various sediment types is sufficient to strongly suggest a methodology for classification of sediments into several distinctive categories. It is evident that sand and gravel stands at one end of the gain spectrum, and hence is likely to be identifiable by oblique methods.

Computer analyses have helped us also quantify from a theoretical viewpoint the correlations between various analytical models. An important result obtained is that the substantial difference exists between the various theoretical models at higher angles of acoustic energy incidence, i.e. between ray theory and field theory approaches for example. This fact, coupled with the predictions for the "Hamilton" soils, suggests the importance of oblique profiling in submarine soils classification and identification, and appropriate model selection.

These computer studies have been of vital importance in developing useful theoretical approaches to the acoustical classification of sedimentary types, an essential tool to the development of a mineral resource technology. The computer work also has resulted in other technical progress, such as a general theory for compensation acoustic transducers, which is a direct product of this research effort.[15]

Soil Mechanics and Geomorphology

The main activity of this task area within the project has been the acquisition of experimental soil mechanical data. During the past year we have

1. Developed an improved capability, both in physical facilities and in trained personnel in the analysis of soil mechanical and geomorphological data. A new project-sponsored soils laboratory has been established.

2. A Model II Vibracorer, coring system has been designed, field tested and made operational.

3. A substantial number of marine (up to 25 feet in length) cores have been obtained in sites where acoustic data also has been acquired.

4. The cores have all been analyzed for geomorphological and soil mechanical data as an adjunct to the acoustical-soil mechanical correlation studies.

5. Prototype shear and compressional wave velocimeters have been designed and tested on core samples. The velocimeters are being used in the

correlation studies.

6. Basic theoretical analysis has commenced on the interaction of a dynamic penetrometer with marine soils. The analysis is of an in-situ system for predicting the engineering properties of marine soils.

7. A dynamic core penetrometer has been designed and constructed, for penetrometering test in marine soils down to a depth of ten feet below the ocean bottom. The system will be evaluated when funds become available for this purpose.

Signal Processing of Experimental Acoustic Data

The second year of experimental data collection and analysis was aimed at generating reliable descriptors of the bottom sediments that permit the development of practical systems. During the second year this work accomplished:

1. The generation of an extensive data bank of controlled echoes from six sites taken at five discrete frequencies. Improved methods of wide-dynamic range data recording were evolved.

2. The wide variability attendant to the first year's data assessments was substantially reduced. Techniques to remove boat motion have allowed the scatter in the measured acoustic indices to be traced to spatial variability of the sediments and to reflecting layer roughness. Ensemble averaging have been introduced to increase the confidence level of bottom parameter assessments.

3. We isolated a frequency dependence in the reflection coefficient, that is indicated to relate to sediment type. Dependence, however, appears to be second order.

4. The plane wave model, described in the first year's report was fully programmed on the computer. This model, far less sophisticated

than the field theoretical model, does serve well for processing experimental data. The model was expanded to accomodate oblique incident qeometry and to cope with up to five subbottom layers. It presently forms the basis for extracting compressional wave velocity and layer attenuation coefficients in the third year.

5. Computer programming related to processing of the data bank also received much attention. This included the following routines: Energy Analysis, Reflection Identification, Multiple Pulse Reflected Energy, empirical reflection coefficients and Fourier transform. In addition data manipulative programs for statiscally ensemble averaging, editing and linearization of the logarithmic recording process were developed.

Of the number of acoustic indices found to be of promise, we have isolated four for primary study. They are:

1. Bottom loss magnitude;
2. Attenuation rate as a function of frequency;
3. Compressional velocity;
4. Angular dependence of reflection coefficient.

The second year produced useful correlation of bottom loss with sediment type, which were substantiated by independent Woods Hole experiments. Compression wave velocity values have been extracted from the data base. The analysis of data taken on the angular dependence of reflection have already indicated significant potential relative to the identification and classification of marine sediments to warrant further intensive study along this research line. To this end, a third-year experiment has been designed incorporating measurement of the above acoustic indices.

To summarize, the physical data collection and analysis program has progressed to the point where reliable parameters may be assigned and sediment predictions attempted.

The Development of an Exploration Systems/Technology

One of the long-term objectives of this project is to create a technology for the location, identification, and classification of coastal bottom resources. While the development of instruments and hardware systems to support this technology may be premature at this time, substantial planning effort along these lines have been expended by the project team. The system development is proceeding along these lines:

1. Higher parametric sensitivity will probably be achieved through oblique profiling techniques.
2. Data scatter will most likely be reduced by motion stabilization of the instrumental systems.
3. Acoustic signature identification will undoubtedly utilize statistical techniques to amplify the descriptions for identification of the soils.
4. The system implimentation will rely upon the insights gained from the theoretical model efforts.
5. The system components will be, most likely, conventional.

Environmental/Ecological Impact of Near-Shore Mining of Sand and Gravel

The purpose of the Ecology Section of the University of New Hampshire-Raytheon Company Sea Grant Program is to study the environmental effects of sand and gravel mining on marine pelagic and benthic communities. The program, as originally proposed, was to be an ecological impact study of commercial dredging operation in Massachusetts Bay in order to provide baseline information on the effects of such operations on marine communities, if any, and to work with industry and state and federal agencies to develop criteria which would minimize potential detrimental effects of such operations. The study is to be done in Massachusetts Bay due to the strong interest on the part of the state government in Massachusetts, particularly the Division of Mineral Resources, to have the necessary ecological impact information to intelligently grant leases within the state's territorial waters.

To determine the environmental effects of marine mining, five interdependent projects to study both pelagic and benthic communities were proposed. The Environmental Systems Center of Raytheon Company was to study Zooplankton and Finfish Communities while the Ecology group at the University of New Hampshire was to do Phytoplankton studies and Benthic Communities, both flora and fauna. The research teams were to share the responsibility for collecting physical and chemical data during their biological sampling program and to exchange information to interrelate the results of each study were planned. Due to funding problems, the Zooplankton and Finfish studies were not begun. A second handicap to the program was the difficulty in finding a dredging operation on which to do an impact study; without a proposed site for a dredge operation to take place in the future, it was impossible to establish baseline study sites.

In order to refine sampling and laboratory techniques and to develop a familiarity with the fauna and flora of Boston Bay, the University of New Hampshire's research teams established a series of stations and began sampling these on a monthly basis during the summer of 1971. Two of the stations established were near the large sand spit off Great Brewster Island where dredging for sand had already occurred and might conceivably be reestablished. The third site was well north of this area and therefore could serve as a control site should a dredging operation be instituted at the Great Brewster Sand Spit. Monthly sampling at these stations continued through the remainder of this year of the program. The phytoplankton program established another four stations running to the mouth of Portsmouth Harbor in New Hampshire in order to provide a broader spectrum of information on the phytoplankton communities. In the main body of this report the techniques of the individual projects and the information collected are summarized. The results of these studies are still being tabulated and specific technical reports will be submitted in the near future as well as reprints of papers submitted for publication.

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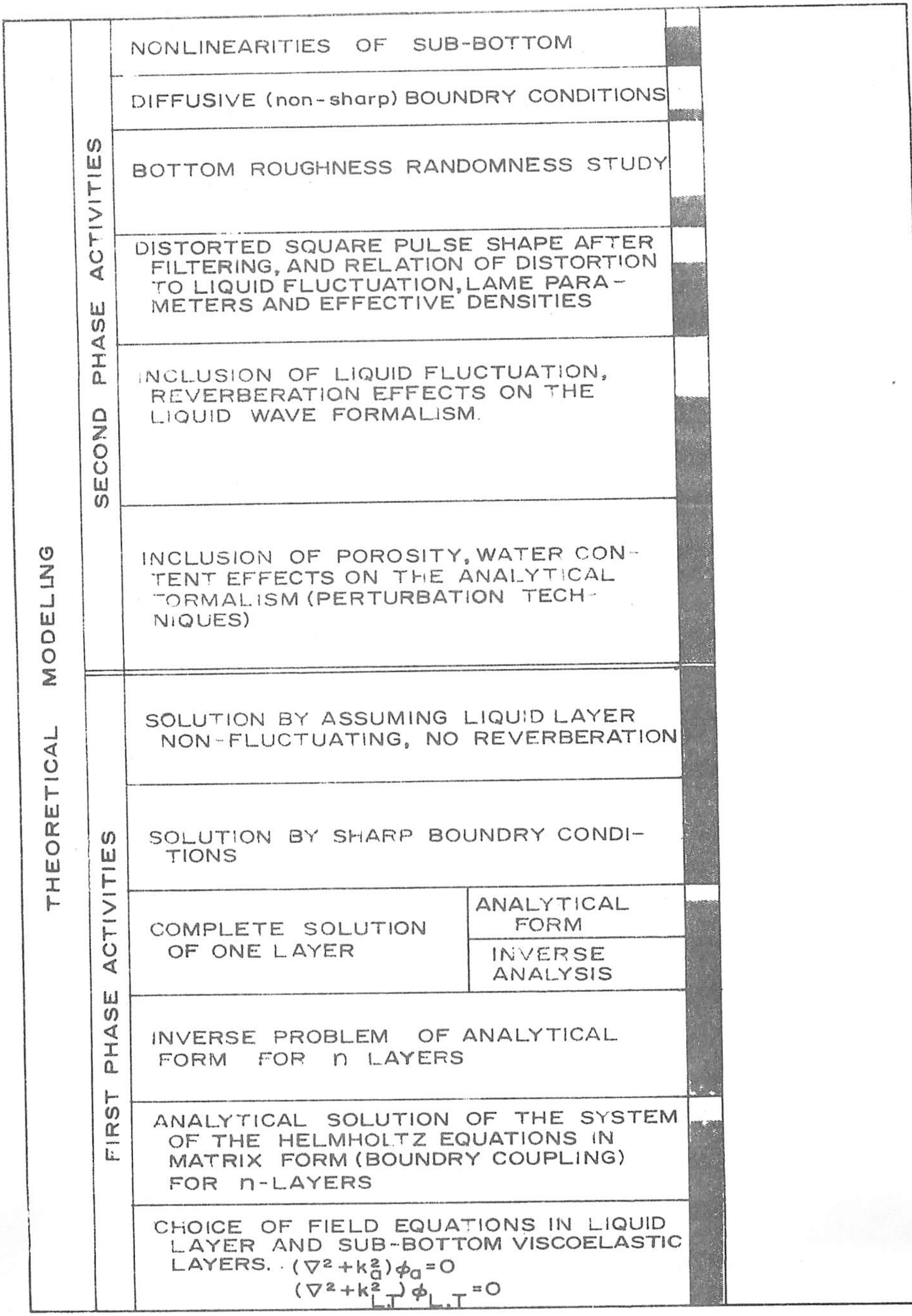
APPENDIX II

Graphic Summaries of Technical Activities

A summary of technical progress activities is presented in a series of figures. The bar graph representations at the right-hand side of the individual activity area descriptors present the June 1972 status. The first and second phases of the four areas of technical study are divided roughly into primary and secondary effects.



THEORETICAL MODELING	SECOND PHASE ACTIVITIES	NONLINEARITIES OF SUB-BOTTOM	
		DIFFUSIVE (non-sharp) BOUNDRY CONDITIONS	
		BOTTOM ROUGHNESS RANDOMNESS STUDY	
		DISTORTED SQUARE PULSE SHAPE AFTER FILTERING, AND RELATION OF DISTORTION TO LIQUID FLUCTUATION, LAME PARAMETERS AND EFFECTIVE DENSITIES	
		INCLUSION OF LIQUID FLUCTUATION, REVERBERATION EFFECTS ON THE LIQUID WAVE FORMALISM.	
		INCLUSION OF POROSITY, WATER CONTENT EFFECTS ON THE ANALYTICAL FORMALISM (PERTURBATION TECHNIQUES)	
	FIRST PHASE ACTIVITIES	SOLUTION BY ASSUMING LIQUID LAYER NON-FLUCTUATING, NO REVERBERATION	
		SOLUTION BY SHARP BOUNDRY CONDITIONS	
		COMPLETE SOLUTION OF ONE LAYER	ANALYTICAL FORM
			INVERSE ANALYSIS
		INVERSE PROBLEM OF ANALYTICAL FORM FOR n LAYERS	
		ANALYTICAL SOLUTION OF THE SYSTEM OF THE HELMHOLTZ EQUATIONS IN MATRIX FORM (BOUNDRY COUPLING) FOR n-LAYERS	
		CHOICE OF FIELD EQUATIONS IN LIQUID LAYER AND SUB-BOTTOM VISCOELASTIC LAYERS. $(\nabla^2+k_a^2)\phi_a=0$ $(\nabla^2+k_{L,T}^2)\phi_{L,T}=0$	

Figure A - Description and Status of Theoretical Modeling Activities.

SOIL MECHANICS & GEOMORPHOLOGY	SECOND PHASE ACTIVITIES	EXPERIMENTAL	CORE SAMPLE DIRECT DATA ANALYSIS	▨
			VIBRATORY TEST BY VELOCIMETERS OF CYLINDRICAL CORE SAMPLE	
			CORE DATA SAMPLING (POSSIBLY RICHARDSON CORING)	
		THEORETICAL	VIBRATION ANALYSIS OF CORE SAMPLE OF HETEROGENEOUS SUB-BOTTOM MATERIAL	▨
			SAND, CLAY, GRAVEL, MINERAL SUB-BOTTOM SOIL IDENTIFCATION BY ACOUTIC SIGNATURES	
			SAND, CLAY, GRAVEL, MINERAL, SUB-BOTTOM SOIL PARAMETERIZATION	▨
			HETEROGENEOUS SUB-BOTTOM SOIL STUDIES (GENERAL)	▨
			MICROSTRUCTURE STUDIES (GENERAL)	▨
	FIRST PHASE ACTIVITIES	EXPERIMENTAL	DIRECT LAB TESTS FOR GRAIN SIZE WATER CONTENT, POROSITY, ETC. FROM CORE SAMPLES	▨
			CORE DATA SAMPLING	▨
		THEORETICAL	VIBRATION ANALYSIS OF CYLINDRICAL CORE SAMPLES	▨
			ATTENUATION EFFECTS IN THE LAMÉ PARAMETERS	▨
			RIGIDITY VERSUS GRAIN STRUCTURE RELATION IN LAME PARAMETERS λ, μ	▨
			INCLUSION OF WATER CONTENT INTO THE FIELD EQUATIONS $\rho = \rho_o(1-\gamma) + \rho\gamma_L$	▨
			INCLUSION OF POROSITY EFFECTS INTO THE FIELD EQUATION $\rho = \rho_o(1-\gamma)$	▨
			CHOICE OF FIELD EQUATION IN THE SUB-BOTTOM LAYERS $\rho \frac{\partial^2 \vec{u}}{\partial t^2} - \mu\nabla^2\vec{u} - (\lambda+\mu)\nabla(\nabla \vec{u}) = 0$	▨

Figure B - Description and Status of Soil Mechanics and Geomorphology.

SIGNAL PROCESSING	SECOND PHASE ACTIVITIES	INTERP OF DATA	INTERPRETATION OF DISTORTED SQUARE PULSE SHAPE IN TERMS OF THEORETICAL MODEL
		DATA COLLECTION	DATA COLLECTION FOR SOURCE AND RECEIVER ON BOTTOM SURFACE
		NUMERICAL ANAL & COMPUTATION	COMPUTER ANALYSIS OF nth ORDER COUPLED EQUATIONS
			FAST FOURIER TRANSFORM TECHNIQUES
		THEORETICAL	ADAPTATION OF INPUT-OUTPUT RELATION INTO KALMAN FILTER OF n LAYERS
			ADAPTATION OF INPUT-OUTPUT RELATION INTO KALMAN FILTER OF ONE LAYER
			ADAPTING WIENER FILTER TO KALMAN FILTER
	FIRST PHASE ACTIVITIES	INTERP OF DATA	PLANE WAVE REFLECTION COEFFICIENTS
		DATA COLLECTION	ACOUSTICAL PROFILING
			TIME RESPONSE TO MODULATED PULSE
		NUMERICAL ANALYSIS AND COMPUTATION	COMPUTER ANALYSIS OF THE SYSTEM NOISE FIELD
			INVERSION OF MATRIX OF ANALYTICAL FORM BY COMPUTER ANALYSIS
			INCLUSION OF NOISE FIELDS(REVERBERATION, BOTTOM ROUGHNESS, LIQUID INHOMOGENEITY, FLUCTUATION OF LIQUID ITSELF, SUB-BOTTOM
		THEORETICAL EFFORTS	STATISTICAL ANALYSIS
			INPUT-OUTPUT RELATION-ANALYTICAL FORM FOR n LAYERS IN MATRIX FORM
			INPUT-OUTPUT RELATION-ANALYTICAL FORM FOR ONE LAYER $\phi_{out}(\vec{k},\omega)=\frac{\Delta_1(\vec{k},\omega)}{\Delta(\vec{k},\omega)}\phi_{in}(\vec{k},\omega)$
			CHOICE OF OPTIMIZED FILTER (WIENER FILTER $\phi_{out}=\int h(t-T)\,\phi_{in}(T)\,dT$

Figure C - Description and Status of Signal Processing Activities.

ACOUSTIC DATA ACQUISITION					
	SECOND PHASE	NEW ENGLAND COAST	REFLECTION TEST, TRANSDUCERS ON BOTTOM	▨	
			PROFILING	▨	
			PULSE TESTING	▨	
		NARRAGANSETT BAY	REFLECTION TESTS, TRANSDUCERS ON BOTTOM.	▨	
			PROFILING	▨	
			PULSE TESTING	▨	
	FIRST PHASE	NARRAGANSETT BAY	PROFILING	▨	
			PULSE TESTING	▨	
		LONG ISLAND SOUND SURVEY	PROFILING	▨	
			PULSE TESTING	▨	

Figure D - Description and Status of Acoustic Data Acquisition.

APPENDIX III

Part A

SOUND PROPAGATION IN A SEMI-INFINITE LIQUID OVERLYING A HOMOGENEOUS VISCOELASTIC HALFSPACE

ALLEN H. MAGNUSON

Abstract

Approximate results are obtained for the acoustic response due to a steady-state point source in a semi-infinite liquid overlying a viscoelastic halfspace. The study is intended for application to the acoustic classification of sediments on the continental shelf. The response in the acoustic field is formulated as a Green's function expressed in an integral form. The integral is evaluated approximately for two cases corresponding to two types of experiment: one for near-bottom testing, and the other for oblique-incidence testing in the radiation zone. Evaluation of the integral yields various expressions, each representing the leading term in an asymptotic expansion. The terms are interpreted physically as reflected, lateral (refracted) and surface waves. The types of response for both cases are discussed and compared with previous results.

Introduction

In the past few years, interest has developed in extracting mineral sediments, particularly sand and gravel, from the continental shelf. This interest has stimulated a demand for a rapid and inexpensive means for identifying or classifying these sediments. In addition to the identification and classification problem, data is needed on the sediment's load-bearing capacity, shear strength and related properties for offshore construction projects.

This paper develops an acoustical model for the ocean-sediment system. The analytical results indicate the feasibility of classification of ocean sediments by means of their viscoelastic parameters (complex Lamé constants). After the sediment is classified, its engineering properties can be determined indirectly; however, this is a problem beyond the scope of the present paper.

We are interested in modeling two types of acoustic sounding: 1) Near-bottom testing, where an array of acoustic transducers is lowered to the ocean floor from a survey vessel, and 2) Oblique incidence testing, where transducers are hung over the side of the vessel and are kept relatively close to the water surface. In both cases modulated short-pulse testing is of interest with pulse lengths of about one msec and carrier frequencies from 3 to 20 kHz. In addition, water depths vary from 50 to 600 ft. For this type of testing, the length of the pulse propagating in the water is much smaller than the water depth. The effect of the water's free surface can be ignored in the subsequent analysis, since surface reflections either occur well after first returns, or they can be separately identified and ignored in the analysis of the data. The liquid layer, then, is considered to be of infinite depth.

Considerable data on the elastic properties of ocean sediments has been obtained and summarized by Hamilton in Ref. (1). His results indicate that the compressional wave propagation speed (c_L) varies from 1 to 1.3 times the speed of sound in the water (c_0), and the shear wave speed (c_T) is considerably smaller than either c_0 or c_L or

$$c_L > c_0 > c_T$$

Data on the damping in the bottom is not as extensive (see, for example Refs. (2), (3) and (4)). It is known that the damping for the frequency range of interest is small. In this paper Voigt-type damping is assumed. It is modeled by taking the Lamé parameters λ and μ as operators of the form

$$\lambda = \lambda' + \lambda'' \frac{\partial}{\partial t} .$$

Experimental results, notably Ref. (4), indicate that the actual sediment damping corresponds to a constant phase lag modeled in the frequency domain as

$$\lambda = \lambda' + i\lambda'',$$

$$\mu = \mu' + i\mu''$$

Nevertheless, the Voigt model is used here because the energy content of the acoustic pulse is concentrated near the carrier frequency. The precise form of the damping is not important in this case. In addition, Voigt damping has a simple time-domain representation.

The work presented here is closely related to studies of seismic waves propagating in the ocean floor(5). The results obtained in reference (5) do not apply directly to the problem posed here for two reasons: 1) The deep ocean bottom is solid (basaltic or granitic), where $c_0 < c_T < c_L$, and damping is negligible, and 2) modal propagation predominates since, typically, the receiver is located far from the disturbance relative to the water depth. Modal propagation implies waveguide behavior where surface and bottom

Note: This Appendix, in essentially the form given here, was presented by the author at the IEEE Ocean '72 Meeting in Newport, Rhode Island (Sept. 1972).

reflections interfere constructively.

The acoustical response in a semi-infinite liquid medium overlying a damped elastic solid halfspace due to a monopole point source is derived using a Green's function formalism. The monopole source is located at a point (0, z'). Field points of the acoustic response are at points (r, z) as shown in Figure (1). The monopole represents the noise source used to excite the acoustic field and the points (r, z) represent possible locations of the receiver.

Green's Function Evaluation By Integration In The Complex Plane

The Green's function $G(r, z, z', \omega)$ representing the acoustic response is derived in the Appendix. It is expressed in Eq. (A-8) of the Appendix as the sum of three terms: the direct wave, an image wave and a residual term (ϕ_0') as follows:

$$G(r,z,z',\omega) = \frac{1}{4\pi}\frac{e^{-ik_0R}}{R} + \frac{1}{4\pi}\frac{e^{-ik_0R_I}}{R_I} + \phi_0'(r,z,z',\omega). \qquad \text{(A-8)}$$

We wish to evaluate the integral form for ϕ_0'. The integral is evaluated approximately for two cases: one representing near-bottom testing, and the other representing oblique-incidence testing in the radiation zone.

The first case is taken by setting $k_0r \gg 1$; i.e., the lateral separation of source and receiver are much larger than the wavelength of sound in the water. Using well-known identities for the Bessel function, we obtain for ϕ_0' in Eq. (A-8) a Fourier integral in a large parameter k_0r (7):

$$\phi_0' = -\frac{1}{4\pi}\sqrt{\frac{2}{\pi r}}\, e^{i\pi/4}\int_{-\infty}^{\infty} e^{-ik_0r\left(\frac{\zeta}{k_0}\right)} \times \left\{\frac{e^{-a_0(z+z')}\, a_L\sqrt{\zeta}}{a_0 D(\zeta)}\right\} d\zeta \qquad (1)$$

where $D(\zeta) = ma_0\left[\left(\frac{2\zeta^2}{k_T^2} - 1\right)^2 - \frac{4a_La_T\zeta^2}{k_T^4}\right] + a_L$.

Eq. (1) is evaluated by integration in the complex plane $\xi = \zeta + i\eta$ using the contour shown in Fig. (2). The integral along the real line is replaced with integrals around the branch cuts and a residue term:

$$\phi_0' = -\{I_{\Gamma_T} + I_{\Gamma_0} + I_{\Gamma_L} + 2\pi i(\text{Residue})\} \qquad (2)$$

where I_{Γ_T}, I_{Γ_0}, I_{Γ_L} are path integrals around the cuts for $\xi = k_T, k_0, k_2$ or $a_T=0$, $a_0=0$, $a_L=0$.

The path integrals around the branch cuts are evaluated by changing variables as follows:

$\xi = k(1 - is)$ on right side of cut,

$\xi = k(1 - ise^{i2\pi})$ on left side of cut,

where $k = k_T, k_0, k_L$. The quantities a_T, a_0, a_L change signs on the left side of the respective cuts. Each integral becomes a line integral in s with a rapid exponential decay in the integrand for increasing s. For large k_0r, k_Lr, k_Tr, the line integrals become approximately

$$I_{\Gamma_T} \cong \frac{1}{4\pi}\frac{e^{i\pi/2}}{r^2k_T}\frac{8m(k_T^2 - k_L^2)}{\left\{m\sqrt{k_T^2-k_0^2} + \sqrt{k_T^2-k_L^2}\right\}^2} e^{-ik_Tr} \times e^{-\sqrt{k_T^2-k_0^2}\,(z+z')} \qquad \text{(3-a)}$$

$$I_{\Gamma_0} \cong \frac{2}{4\pi}\frac{e^{-ik_0r}}{r} \qquad \text{(3-b)}$$

$$I_{\Gamma_L} \cong \frac{1}{4\pi}\frac{2k_Li}{r^2}\frac{1}{m(k_0^2-k_L^2)\left(\frac{2k_L^2}{k_T^2} - 1\right)^2} \times e^{-i[k_Lr+\sqrt{k_0^2-k_L^2}\,(z+z')]} \qquad \text{(3-c)}$$

Eqs. (3-a and c) agree with Honda and Nakamura's (7) results (their Eqs. (21) and (17)), except that here k_T and k_L are complex.

The result (3-b) cancels the direct and image source wave to the first order; i.e., if $z, z' \ll r$. This result is analogous to the Lloyd mirror effect, as noted in Ref. (5), p. 96, and would be expected due to the Green's function being even in a_0 in Eq. (A-7).

Eq. (3-a) is a damped surface wave which decays exponentially as the distance from the interface, and which spreads with a $1/r^2$ dependence.
Eq. (3-c) is a damped wave referred to as a lateral or head wave (8), (9). This wave travels along a path shown in Fig. (3), and is the first wave to arrive at the receiver.

The residue term in Eq. (2) may be written

$$\begin{aligned}(\phi_0)_{\text{Res}} &= -2\pi i(\text{Residue}) \\ &= -2\pi i\left\{-\frac{1}{4\pi}\sqrt{\frac{2}{\pi r}}\, e^{i\pi/4}\, e^{-\xi_sr} \times \frac{e^{-\sqrt{\xi_s^2-k_0^2}\,(z+z')}\, a_L\sqrt{\xi_s}}{a_0\frac{d}{d\xi_s}[D(\xi_s)]}\right\}.\end{aligned} \qquad (4)$$

Where ξ_s is the complex zero of $D(\xi)$, or

$$D(\xi_s) = 0. \qquad \text{(4-a)}$$

Eq. (4-a) may be solved approximately for small damping by expanding $D(\xi_s)$ about the undamped equation. We set

$\xi_s = \xi_{s0} - i\epsilon\xi_s'$,

$k_L = k_{L0} - i\epsilon k_L'$ and

$$k_T = k_{T0} - i\epsilon k_T' ,$$

where $\epsilon \ll 1$. Eq. (4-a) becomes

$$D(\xi_s) = D(\xi_{s0}, k_{L0}, k_{T0}) + \left. -i\epsilon\left\{\left[\frac{d}{d\xi} D(\xi)\right]\xi_s' + \left[\frac{d}{dk_L} D(\xi)\right]k_L' + \left[\frac{d}{dk_T} D(\xi)\right]k_T'\right\} \right|_{\substack{\xi = \xi_{s0}\\ k_L = k_{L0}\\ k_T = k_{T0}}} + \dots = 0$$

To the first order, we have

$$D(\xi_{s0}, k_{L0}, k_{T0}) = 0 \tag{5-a}$$

and

$$\xi_s' = \left[\frac{-\left\{\left[\frac{d}{dk_L} D(\xi)\right]k_L' + \left[\frac{d}{dk_T} D(\xi)\right]k_T'\right\}}{\frac{d}{d\xi}\left[D(\xi)\right]}\right]_{\substack{\xi = \xi_{s0}\\ k_L = k_{L0}\\ k_T = k_{T0}}} \tag{5-b}$$

Solutions to Eq. (5-a) (the undamped equation) are tabulated in Ref. (10). Eq. (5-b) gives the damping of the surface wave in terms of the damping of the longitudinal and shear waves in the bottom. The residue term, then, represents a damped Stoneley wave that spreads cylindrically $(1/\sqrt{r})$, and decays exponentially as the distance from the interface.

Summarizing, the approximate Green's function (Eq. A-7) becomes, from Eqs. (A-8), (2), (3) and (4)

$$\begin{aligned}
G(r,z,z',\omega) &= \\
&= \frac{-1}{4\pi}\frac{e^{i\pi/2}}{r^2 k_T}\left\{\frac{8m(k_T^2 - k_L^2)}{\left\{m\sqrt{k_T^2-k_0^2} + \sqrt{k_T^2-k_L^2}\right\}^2}\right\} \times \\
&\times e^{-ik_T r}\, e^{-\sqrt{k_T^2-k_0^2}\,(z+z')} + \frac{-1}{4\pi}\frac{2k_L i}{r^2} \times \\
&\times\left\{\frac{1}{m(k_0^2-k_L^2)\left(\frac{2k_L^2}{k_T^2} - 1\right)^2}\right\} e^{-i\left[k_L r+\sqrt{k_0^2-k_L^2}\,(z+z')\right]} + \\
&+ \frac{i}{2}\sqrt{\frac{2}{\pi r}}\, e^{i\pi/4}\, e^{-\xi_s r}\left\{\frac{e^{-\sqrt{\xi_s^2-k_0^2}\,(z+z')}\sqrt{\xi_s^2-k_L^2}\,\sqrt{\xi_s}}{\sqrt{\xi_s^2-k_0^2}\,\frac{d}{d\xi_s}\left[D(\xi_s)\right]}\right\} + \\
&+ \dots \quad .
\end{aligned} \tag{6}$$

for $k_0 r \gg 1$ and $r \gg z, z'$, or near bottom testing.

Oblique Incidence Testing

For oblique incidence testing in the radiation zone, we take

$$k_0 r \gg 1, \quad k_0(z+z') \gg 1 .$$

One may write the exponential terms in the integrand of Eq. (1) as

$$e^{-k_0 R_I f(\zeta/k_0)} ,$$

where $f(\zeta/k_0) = i\left[\sqrt{1-(\zeta/k_0)^2}\cos\theta + \sin\theta(\zeta/k_0)\right]$

and $k_0 R_I$ is a large parameter. Now, $f(\zeta/k_0)$ has a saddle point at

$$\zeta_0 = k_0 \sin\theta,$$

$$\eta_0 = 0,$$

where $\sin\theta = r/R_I$ (from Fig. (1)).

The path of integration of Eq. (1) is deformed to a path of steepest descent as shown in Fig. (4). The result differs, depending upon the angle of incidence θ. If $\theta < \theta_c$, where the critical angle θ_c is given by:

$$\theta_c = \sin^{-1}\left[\frac{|\mathrm{Re}\{k_L\}| + |\mathrm{Im}\{k_L\}|}{k_0}\right] , \tag{7}$$

no refracted wave occurs (Fig. (4-a)), and the integration gives approximately

$$\phi_0' = \frac{-1}{4\pi}\frac{2e^{-ik_0 R_I}}{R_I}\frac{\sqrt{\zeta_0^2-k_L^2}}{D(\zeta_0^2)} . \tag{8}$$

Substituting Eq. (8) into (A-8), and manipulating, we obtain for the Green's function:

$$G(r,z,z',\omega) \cong \frac{1}{4\pi}\left\{\frac{1}{R}e^{-ik_0 R} + \frac{N}{D}\frac{1}{R_I}e^{-ik_0 R_I}\right\} , \tag{9}$$

where N/D is the plane-wave reflection coefficient given as

$$\frac{N}{D}(\theta) = \frac{f_1 - f_2}{f_1 + f_2} ,$$

where

$$f_1 = m\cos\theta\left[\left(2\frac{k_0^2\sin^2\theta}{k_T^2} - 1\right)^2 + \frac{4k_0^4\sin^2\theta}{k_T^4} \times \left(\frac{k_L^2}{k_0^2} - \sin^2\theta\right)^{1/2}\left(\frac{k_T^2}{k_0^2} - \sin^2\theta\right)^{1/2}\right] \text{ and}$$

$$f_2 = \left(\frac{k_L^2}{k_0^2} - \sin^2\theta\right)^{1/2} .$$

Eq. (9) shows that the response is a direct wave plus a reflected wave, where the reflection coefficient is the classical result (Ref. 5, p. 79) for a plane acoustic wave reflecting off a solid halfspace.

Now, if $\theta > \theta_c$, the deformed path of integration includes a loop around the branch cut for $a_L = 0$ (Fig. (4-b)). The loop contribution physically represents the refracted wave already computed for the near-bottom case. The Green's function for $\theta > \theta_c$ (but not too near θ_c (9)) is obtained by adding to Eq. (9) the negative of I_{Γ_L} given in Eq. (3-c), or:

$$G(r,z,z',\omega) \cong$$

$$\cong \frac{1}{4\pi}\left[\frac{1}{R}\, e^{-ik_0 R} + \frac{N}{D}(\zeta_\theta^2)\,\frac{1}{R_I}\, e^{-ik_0 R_I} + - \frac{2k_L i}{r^2}\left\{\frac{1}{m(k_0^2-k_L^2)\left(\frac{2k_L^2}{k_T^2}-1\right)^2}\right\} \times e^{-i\{k_L r + \sqrt{k_0^2-k_L^2}\,(z+z')\}}\right] . \tag{9-a}$$

We note from Fig. (4) that the refracted wave first occurs when $\xi = k_L$. The expression for θ_c given in Eq. (7) is obtained by noting that the deformed path Γ_s is inclined 45° from the real axis near ζ_0. One notes that the effect of damping in the bottom is to delay the occurence of the refracted wave. Eq. (7) for the critical angle reduces to the classical result for no damping; i.e.,

$$(\theta_c)_{\text{undamped}} = \sin^{-1}(c_0/c_L) \quad .$$

Discussion of Results

The acoustic response expressed as an approximate Green's function is given for the near-bottom case in Eq. (6). Three terms appear:

1) A damped interface wave propagating at approximately the speed of the shear wave velocity in the bottom and with a $1/r^2$ dependence,

2) A damped lateral wave associated with the compressional wave in the bottom, with a $1/r^2$ dependence, and

3) A damped Stoneley (interface) wave with a cylindrical $(1/\sqrt{r}\,)$ spreading.

The expression for the first two waves agrees with the results of previous investigators(7), except that here damping occurs because k_L and k_T are complex, and term (1) is not a lateral wave since $|k_T|>k_0$. (In Ref. (7), two lateral waves occur, since both k_L and k_T were taken less than k_0.) In addition, Ref. (7) did not consider the Stoneley wave. An expression (Eq. (5-b)) has been developed for the damping of the Stoneley wave using a small damping assumption and a perturbation approach.

These results may be applied to the subbottom classification problem in the following manner:

1) The Stoneley wave velocity and damping may be determined experimentally from pulse testing (after a Fourier synthesis has been performed for the particular pulse shape). This technique is in use currently(11), and was used to infer shear wave velocities presented in Ref. (1). Damping was not considered in previous analyses. The result obtained here is three-dimensional (point source) and damping is included explicitly.

2) The compressional wave velocity (c_L) may be obtained directly by timing the "first arrival" at the receiver (the first arrival being the lateral wave.) This technique is widely used in the geophysics field.

The results for the oblique incidence case are given by Eqs. (9) and (9-a). Three types of response occur:

1) The direct wave traveling from source to receiver through the water.

2) The reflected wave with angle of incidence $\theta = \tan^{-1}[r/(z+z')]$ (Fig. (1)), and reflection coefficient $\frac{N}{D}(\theta)$.

3) The lateral wave associated with the compressional wave in the subbottom, which occurs for angles of incidence beyond a critical angle θ_c given by Eq. (7).

Information on the subbottom may be inferred from measurement of the reflection coefficient $\frac{N}{D}$ obtained by analyzing the reflected wave. This approach was successfully used by Breslau(12). Later, Faas(13) proposed a linear relationship between reflection coefficient at normal incidence ($\theta=0$) and sediment porosities, and Hamilton(14) presented data relating bottom impedance $(\rho_1 c^{L}_2)$ and reflection coefficient at normal incidence to porosity and density. The disadvantage to this approach is that one only obtains information on the subbottom impedance. More detailed analysis of the reflected wave term (including damping) in Eqs. (9) and (9-a) for the oblique incidence case ($\theta>0$) may yield more detailed information.

Analysis of the lateral wave is probably impractical for oblique incidence testing (transducers near the surface) because the critical angle for sedimentary bottoms is quite large (approaching 90°). This implies that a very wide separation between source and receiver is required to observe the wave.

Some new results are presented here. First, the effect of damping in the subbottom has been treated. The main result of inclusion of damping is that the response has exponential decay (except for the direct and reflected wave). It is shown that the appearance of the lateral wave is delayed by the inclusion of damping; i.e., the critical angle is larger than the undamped critical angle. An expression is given for the damping of the Stoneley wave for small damping.

Second, the integral form for the Green's function has been evaluated for near-bottom testing and oblique incidence testing, and both results have been compared. The separation of the integration into these two cases provides clearer insight into the problem; in particular, why different types of wave occur near the bottom and in the oblique incidence radiation zone.

Further development of the analysis is planned. In particular:

1) Fourier synthesis for practical pulse shapes and computer studies for the acoustic response pulses for specific test geometries.

2) Analysis of higher-order terms in the asymptotic expansions for the Green's function.

3) Computation of the effect of random inhomogenieties and surface roughness on the acoustic response.

Acknowledgements

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Appendix. Derivation of the Green's Function Representing The Acoustic Response

In the liquid, the governing equation is:

$$[\nabla^2 - \frac{1}{c_0^2}\partial_t^2]\phi_0(\vec{r}, t) = -\psi(\vec{r}, t) , \qquad \text{(A-1)}$$

where c_0, ϕ_0, ψ are the speed of sound in the liquid, the displacement potential, and the force potential. The displacement and the body force per unit mass in the liquid are given by:

$$\vec{u}_0 = \nabla\phi_0 ,$$

and $\vec{F} = c_0^2\nabla\psi$.

A monopole point source distribution in the liquid is introduced as shown in Fig. (1) by setting

$$\psi(\vec{r}, t) = \frac{\delta(r)}{2\pi r}\,\delta(z-z')e^{i\omega t},$$

where δ is the Dirac delta function, and a harmonic time dependence has been taken. Eq. (A-1) becomes, suppressing the time dependence:

$$(\nabla^2 + k_0^2)G(\vec{r}, \omega) = -\frac{\delta(r)\delta(z-z')}{2\pi r} , \qquad \text{(A-2)}$$

where $k_0 = \frac{\omega}{c_0}$

and $G(\vec{r}, \omega) = G(r, z, z', \omega)$ is the Green's function for the liquid field $(z > 0)$.

The governing equation for the solid is written, for the harmonic time dependence:

$$\rho_1\omega^2\vec{u}_1 + \mu\nabla^2\vec{u}_1 + (\lambda+\mu)\nabla(\nabla\cdot\vec{u}_1) = 0 , \qquad \text{(A-3)}$$

where ρ_1, $\vec{u}_1$, μ, λ are the solid's density, displacement and Lamé constants. Viscoelasticity is introduced by taking λ and μ in the frequency domain as:

$$\lambda = \lambda' + i\omega\lambda''$$

and

$$\mu = \mu' + i\omega\mu''$$

Eq. (A-3) may be written in the following form:

$$(\nabla^2 + k_T^2)\vec{u}_1 + (\frac{k_T^2}{k_L^2} - 1)\nabla(\nabla\cdot\vec{u}_1) = 0, \qquad \text{(A-4)}$$

where $k_T^2 = \frac{\omega^2}{c_T^2+i\omega b_T}$, $k_L^2 = \frac{\omega^2}{c_L^2+i\omega b_L}$

and $c_T^2 = \mu'/\rho_1$, $c_L^2 = \frac{\lambda'+2\mu}{\rho_1}$, $b_T = \frac{\mu''}{\rho_1}$,

$$b_L = \frac{\lambda''+2\mu''}{\rho_1} .$$

One may also write, for small damping ($\varepsilon \ll 1$)

$$k_T = \pm(k_{T_0} - i\varepsilon k_T') ,$$

$$k_L = \pm(k_{L_0} - i\varepsilon k_L') ,$$

where k_{T_0}, k_{L_0}, k_T', k_L' are positive quantities of the same order.

Solutions to Eq. (A-4) may be written

$$\vec{u}_{1L} = \nabla\phi_L ,$$

$$\vec{u}_{1T} = \nabla\times\nabla\times(\hat{e}_z\phi_T)$$

and $\vec{u}_1 = \vec{u}_{1L} + \vec{u}_{1T}$,

where $\nabla\times\vec{u}_L = 0$, $\nabla\cdot\vec{u}_T = 0$, and $\hat{e}_z$ is the unit vector in the z-direction. The scalar functions ϕ_L and ϕ_T satisfy the following scalar Helmholtz equations:

$$(\nabla^2 + k_L^2)\phi_L = 0 , \qquad \text{(A-5)}$$

and

$$(\nabla^2 + k_T^2)\phi_T = 0 . \qquad \text{(A-6)}$$

The problem reduces to that of solving scalar equations (A-2), (A-5), and (A-6) subject to appropriate boundary conditions. The boundary conditions that apply at the liquid-solid interface are:

i) $u_{0z} = u_{1z}$ (continuity of displacement),

ii) $(\sigma_{zz})_0 = (\sigma_{zz})_1$ (continuity of normal stress)

and

iii) $(\sigma_{rz})_1 = 0$ (zero shear stress).

The Green's function satisfying the boundary conditions and the governing equations may be constructed using standard techniques[(15),(16)]:

$$G(r,z,z',\omega) = \frac{1}{2\pi}\int_0^\infty \frac{J_0(\zeta r)e^{-a_0(z_>)}}{a_0}\,\frac{N(\zeta)}{D(\zeta)}\,\zeta d\zeta, \qquad \text{(A-7)}$$

where $D(\zeta) = ma_0\left[(\frac{2\zeta^2}{k_T^2} - 1)^2 - \frac{4a_La_T\zeta^2}{k_T^4}\right] + a_L,$

$$N(\zeta) = ma_0\left[(\frac{2\zeta^2}{k_T^2} - 1)^2 - \frac{4a_La_T\zeta^2}{k_T^4}\right]\cosh(a_0z_<) +$$

$$+ a_L\sinh(a_0z_<),$$

$$z_> = \mathrm{Max}(z,z') , \quad z_< = \mathrm{Min}(z,z'),$$

$$a_0 = (\zeta^2 - k_0^2)^{1/2}, \quad a_L = (\zeta^2 - k_L^2)^{1/2},$$

$$a_T = (\zeta^2 - k_T^2)^{1/2}, \quad m = \rho_1/\rho_0 \,.$$

Eq. (A-7) may be manipulated into a more convenient form using Sommerfeld's(17) integral form for a point source:

$$G(r,z,z',\omega) = \frac{1}{4\pi}\left\{\frac{e^{-ik_0R_I}}{R} + \frac{e^{-ik_0R_I}}{R_I}\right\} + \\ + \phi_0'(r,z,z',\omega) \qquad \text{(A-8)}$$

where

$$R = [(z-z')^2 + r^2]^{1/2}, \quad R_I = [(z+z')^2 + r^2]^{1/2}$$

and

$$\phi_0' = -\frac{1}{2\pi}\int_0^\infty \frac{J_0(\zeta r)e^{-a_0(z+z')}\ a_L}{a_0D(\zeta)}\,\zeta d\zeta$$

The first term in Eq. (A-8) is the direct wave, the second term is an image source term (Fig.(1)), and the third is a residual term that must be evaluated by integration in the complex plane.

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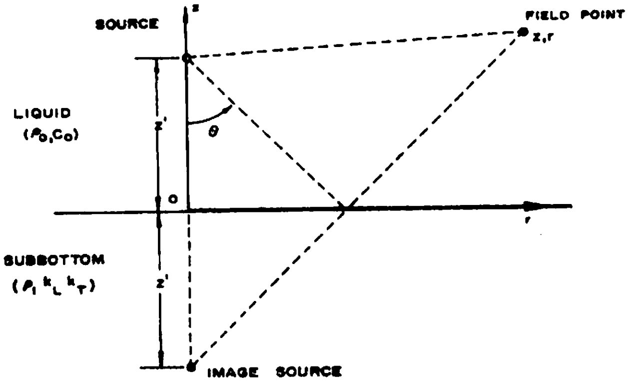


Figure 1. The Geometry of the Liquid-Subbottom Field

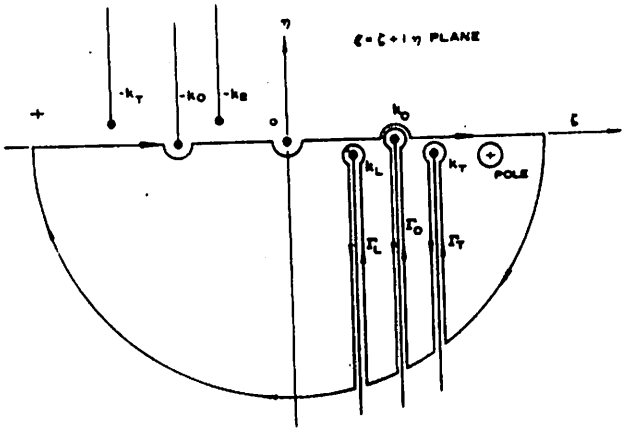


Figure 2. Contour for Integration for the Near-Bottom Case: $k_0 r >> 1$, $(z+z')/r << 1$.

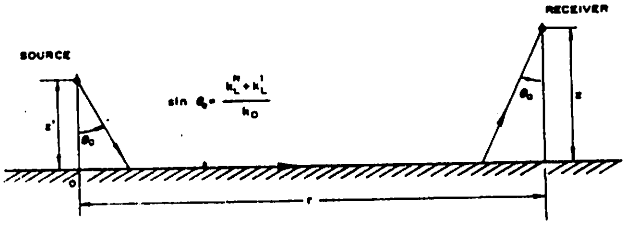
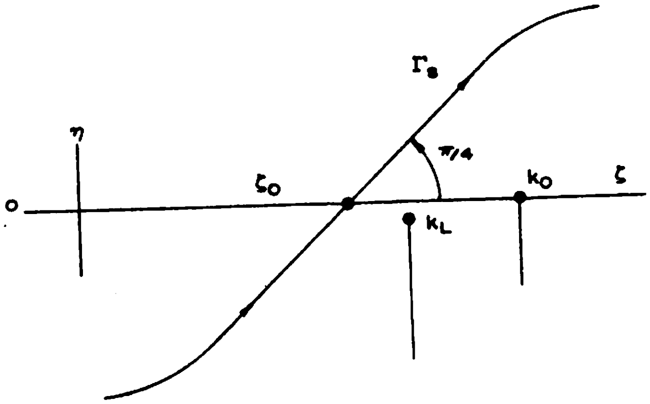
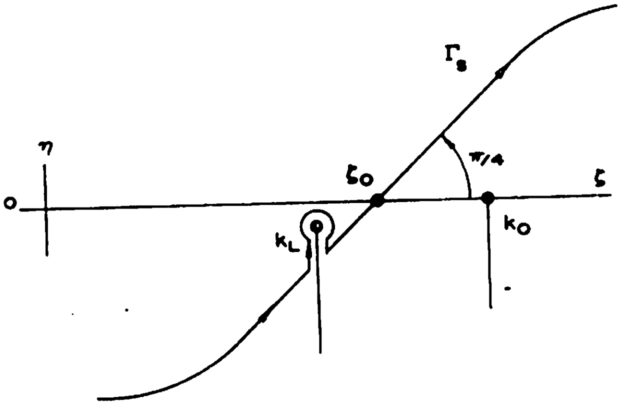


Figure 3. Path of the Refracted Wave



a) No Refracted Wave $(\Theta<\Theta_c)$



b) With Refracted Wave $(\Theta>\Theta_c)$

Figure 4. Steepest Descent Paths in the ξ-Plane for $rk_0>>1$, $(z+z')k_0>>1$.

APPENDIX III

Part B

SOUND PROPAGATION IN A LIQUID LAYER OVERLYING A MULTI-LAYERED VISCOELASTIC HALFSPACE

Allen H. Magnuson
Gary K. Stewart

Abstract

The acoustic response due to a point source in a liquid layer overlying a semi-infinite multi-layered viscoelastic medium is obtained using a Green's function formalism. A matrix recurrence relation, developed from the boundary conditions, is used to relate the scalar wave functions in the last viscoelastic layer to the scalar wave functions in the intermediate layers using (4×4) matrix manipulations. The transformed form of the Green's function is then obtained by applying appropriate boundary conditions at the top and bottom of the liquid layer. The Green's function is then written in integral form convenient for computer evaluation, since the integrand can be computed for many layers using the recurrence relation. Special cases are discussed and compared with known results.

Introduction

The first paper of this series treated the acoustic response of a semi-infinite liquid overlying a homogeneous viscoelastic halfspace (Ref. 1). This paper treats the more general case of a point source in a liquid layer of finite depth overlying a series of n parallel layers of a viscoelastic solid (Fig. 1). Each layer has arbitrary density ρ_j, and complex velocities of wave propagation α_j and β_j. This model corresponds rather closely to the stratification of sediments on the continental shelf. Each subbottom layer is assumed to be a homogeneous, isotropic Voigt solid, described mathematically in the main text of this paper.

This problem and closely related problems have been studied by numerous investigators(2),(3),(4),(5). Jardetsky(2), developed the period equation or dispersion relation for a layered elastic halfspace with a point source in the first layer. The period equation was expressed as a determinant of order (4n-2), where n was the number of elastic layers. He could not obtain the roots of the period equation explicitly due to the algebraic complexity, but he did make an important observation. This was that, of all the 2n branch point singularities, only the two branch line integrals corresponding to the two branch points of the last (semi-infinite) layer contribute to the response. Thus, the total response consists of a residue series (each term of which corresponds to a solution of the period equation) and contributions due to branch line integrals for the branch point singularities of the last (semi-infinite) layer.

Thomson(3) used a matrix formalism for determining the transmission of plane elastic waves through a stratified solid medium. He developed a recurrence relation relating the velocities and stresses in adjoining plates or layers using Snell's law and continuity of particle velocities and stresses at the interface. Successive application of the recurrence relation enabled him to relate the velocities and stresses at the last plate in terms of those of the first plate. Shaw and Bugl(4) pointed out that Thomson used the unnecessarily restrictive assumption that the shear modulus was constant in all the layers. They also mention that Haskell(5) was apparently the first to remove this restriction.

Shaw and Bugl(4) refined the approach of Refs. (3) and (5) by expressing the displacements and stresses in terms of the layer's parameters and then used a more direct matrix formalism. In addition, they considered the effects of viscoelasticity by treating the elastic constants λ and μ as complex quantities.

The present paper closely parallels the approach of Ref. (2), except that the first layer is taken to be a liquid. This enables us to express the response due to the point source using a scalar Green's function formalism(6), (7). We depart from Ref. (2) to develop a recurrence relation between the coefficients of the scalar potentials of adjacent viscoelastic layers by applying boundary conditions at the interface. Successive application of the recurrence relation then enables us to express the coefficients of the first solid layer in terms of the last layer. Finally, boundary conditions are applied at the top and bottom of the liquid layer to obtain the solution for the response in the liquid. The advantage of this approach is that computations involve 4×4 matrices instead of matrices of order (4n-2), where n is the number of solid layers. This makes the formalism ideal for machine computation.

The recurrence relation developed here differs from that of Refs. (3), (4) and (5) in that the problem treated is three-dimensional and the recurrence relation involves coefficients of

Note: This Appendix, in essentially the form given here, was presented by the authors at the IEEE Ocean '72 Meeting in Newport, Rhode Island (Sept. 1972).

scalar potentials instead of displacements and stresses.

Analytical Development

The governing equation in the liquid with a point source at r = 0, z = z' [Fig. (1)] is taken from Eq. (A-2) of the preceding paper(1).

$$(\nabla^2 + k_0^2)G(\vec{r}|\vec{r}',\ \omega) = -\delta(\vec{r}-\vec{r}') \qquad (1)$$

where $\delta(\vec{r}-\vec{r}') = \dfrac{\delta(r)\delta(z-z')}{2\pi r}$,

$G(\vec{r}|\vec{r}',\ \omega) = G(r,z,z',\omega)$,

and $k_0^2 = \omega^2/c_0^2$.

The quantities G and c_0 are the Green's function and the liquid's speed of sound (adiabatic), respectively. The symbol δ is Dirac's delta function. A time dependence of the form $e^{i\omega t}$ is taken throughout, and is omitted for brevity.

The governing equations for the $j^{\underline{th}}$ viscoelastic layer may be written

$$\rho_j\omega^2\vec{u}_j + \mu_j\nabla^2\vec{u}_j + (\lambda_j+\mu_j)\nabla(\nabla\cdot\vec{u}_j) = 0 \qquad (2)$$

where ρ_j, $\vec{u}_j$, μ_j, λ_j are the layer's density, displacement and Lamé parameters. We introduce Voigt viscoelasticity by writing the Lamé parameters in the frequency domain as

$\mu = \mu' + i\omega\mu''$

and

$\lambda = \lambda' + i\omega\lambda''$.

Following Ref. (1), Eq. (2) reduces to two scalar Helmholtz equations:

$$(\nabla^2 + k_{\alpha j}^2)\phi_{\alpha j} = 0 \qquad (2\text{-a})$$

and

$$(\nabla^2 + k_{\beta j}^2)\phi_{\beta j} = 0\ . \qquad (2\text{-b})$$

where $k_{\alpha j}^2 = \dfrac{\omega^2}{\alpha_j^2}$, $k_{\beta j}^2 = \dfrac{\omega^2}{\beta_j^2}$,

the speed of the dilatational wave α_j and the shear wave β_j are given by

$$\alpha_j^2 = \frac{\lambda_j'+2\mu_j'+i\omega(\lambda_j''+2\mu'')}{\rho_j},$$

and

$$\beta_j^2 = \frac{\mu_j'+i\omega\mu_j''}{\rho_j}\ .$$

The displacements may be written as

$$\vec{u}_j = \vec{u}_{\alpha j} + \vec{u}_{\beta j}\ , \qquad (3)$$

where $\vec{u}_{\alpha j} = \nabla\phi_{\alpha j}$,

$\vec{u}_{\beta j} = \nabla\times\nabla\times(\hat{e}_z\phi_{\beta j})$,

$\nabla\cdot\vec{u}_{\beta j} = 0$, $\nabla\times\vec{u}_{\alpha j} = 0$,

and $\hat{e}_z$ is the unit vector in the z-direction.

Solutions to Eqs. (1) and (2) may be obtained conveniently using a Fourier-Bessel transform

$$\underline{A}(\zeta) = \int_0^\infty A(r)J_0(\zeta r)r\,dr \qquad (4\text{-a})$$

and the inverse transform

$$A(r) = \int_0^\infty \underline{A}(\zeta)J_0(\zeta r)\zeta\,d\zeta\ . \qquad (4\text{-b})$$

The lower bar denotes a transformed quantity. Applying the transformation (4-a) to Eq. (1) results in the following differential equation

$$\left[\frac{d^2}{dz^2} - a_0^2\right]\underline{G}(\zeta,z,z') = \frac{-\delta(z-z')}{2\pi} \qquad (5)$$

where $a_0 = \sqrt{\zeta^2 - k_0^2}$.

We write solutions to Eq. (5) above and below the source as

$$\underline{G}_{>} = Pe^{-a_0z} + Qe^{a_0z}\ , \quad z' < z < h_0 \qquad (6\text{-a})$$

$$\underline{G}_{<} = Re^{-a_0z} + Se^{a_0z}\ , \quad 0 < z < z'\ . \qquad (6\text{-b})$$

We may eliminate three of the unknowns in Eqs. (6) using the continuity and jump condition at z=z'(7) and by noting that the pressure, which is proportional to G, vanishes at z=h_0. Eqs. (6-a and b) may then be written as

$$\underline{G}_{<} = \frac{1}{4\pi a_0}\left\{A_0\sinh[a_0(h_0-z)] - 2\sinh[a_0(z'-z)]\right\}, \qquad (6\text{-c})$$

$$\text{and}\quad \underline{G}_{>} = \frac{A_0}{4\pi a_0}\sinh[a_0(h_0-z)]\ , \qquad (6\text{-d})$$

where A_0 is an unknown, as yet, function of ζ to be determined from the boundary conditions at z=0.

Solutions to Eqs. (2-a and b) may be written in transformed form as

$$\underline{\phi}_{\alpha j} = \frac{1}{4\pi a_{\alpha j}}\left\{A_je^{a_{\alpha j}z} + B_je^{-a_{\alpha j}z}\right\}, \qquad (7\text{-a})$$

and

$$\underline{\phi}_{\beta j} = \frac{1}{4\pi a_{\beta j}}\left\{C_je^{a_{\beta j}z} + D_je^{-a_{\beta j}z}\right\}, \qquad (7\text{-b})$$

where $a_{\alpha j} = \sqrt{\zeta^2 - k_{\alpha j}^2}$,

$$a_{\beta j} = \sqrt{\zeta^2 - k^2_{\beta j}} \quad ,$$

and $h_{(j-1)} < z < h_j$. We note that the n^{th} semi-infinite layer has only two terms, as $B_n = 0$, $D_n = 0$, because the potentials must remain finite as $z \to -\infty$. This implies that the A_j and C_j terms in Eqs. (7) represent downward-traveling waves and the B_j and D_j terms represent upward-traveling waves. It follows that the stipulation that $B_n = D_n = 0$ is essentially a radiation condition.

Boundary Conditions

We must evaluate the 4n-2 functions A_j, B_j, C_j, D_j, $j = 1, 2, \ldots n$ in Eq. (7). We do this by applying boundary conditions at each interface between solid layers. We first express the displacements and stresses in terms of the potentials. The displacements in a cylindrical (r, z, θ) coordinate system may be written (taking into account the θ-symmetry) as

$$u_r = \frac{\partial}{\partial r}\left(\phi_\alpha + \frac{\partial \phi_\beta}{\partial z}\right) , \qquad \text{(8-a)}$$

$$u_z = \frac{\partial \phi_\alpha}{\partial z} + \left(k^2_\beta + \frac{\partial^2}{\partial z^2}\right)\phi_\beta , \qquad \text{(8-b)}$$

and

$$u_\theta = 0 \quad . \qquad \text{(8-c)}$$

We write the stress tensor as

$$\sigma_{ik} = \lambda \varepsilon_{\ell\ell}\delta_{ik} + 2\mu\varepsilon_{ik} , \qquad \text{(8-d)}$$

where ε_{ik} is the strain tensor and δ_{ik} is the Kronecker delta. We need the stress components σ_{zz} and σ_{zr}, whose corresponding strains are written as

$$\varepsilon_{zz} = \frac{\partial u_z}{\partial z} \qquad \text{(8-e)}$$

and

$$2\varepsilon_{rz} = \frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \quad . \qquad \text{(8-f)}$$

The boundary conditions are continuity of stress and displacements at the interface. The first follows from the dynamic equations of motion. The second follows from the conservation of mass. For the j^{th} interface, we write

i) $u_{zj} = u_{z(j+1)}$ at $z = -h_j$, (9-a)

ii) $u_{rj} = u_{r(j+1)}$ " , (9-b)

iii) $\sigma_{rzj} = \sigma_{rz(j+1)}$ " , (9-c)

iv) $\sigma_{zzj} = \sigma_{zz(j+1)}$ " . (9-d)

Applying Eqs. (8) to (9) gives a system of equations that may be written in matrix form as

$$[a_j]\,\vec{A}_{j,j} = [a_{(j+1)}]\,\vec{A}_{(j+1),j} \quad , \qquad \text{(10)}$$

where $[a_j]$ is a 4×4 matrix given as:

$$[a_j] = \begin{bmatrix} \rho_j\beta_j^2(2\zeta^2-k^2_{\beta j}) & \rho_j\beta_j^2(2\zeta^2-k^2_{\beta j}) & -2\rho_j\beta_j^2 a_{\beta j}\zeta^2 & 2\rho_j\beta_j^2 a_{\beta j}\zeta^2 \\ -2\rho_j\beta_j^2 a_{\alpha j} & 2\rho_j\beta_j^2 a_{\alpha j} & \rho_j\beta_j^2(2\zeta^2-k^2_{\beta j}) & \rho_j\beta_j^2(2\zeta^2-k^2_{\beta j}) \\ 1 & 1 & -a_{\beta j} & a_{\beta j} \\ -a_{\alpha j} & a_{\alpha j} & \zeta^2 & \zeta^2 \end{bmatrix} \qquad \text{(11-a)}$$

and $\vec{A}_{(j+1),j}$ is a (4×1) column matrix (vector), setting $(j+1) = j'$:

$$\vec{A}_{j',j} = \begin{bmatrix} \dfrac{A_{j'} e^{-a_{\alpha j'} h_j}}{a_{\alpha j'}} \\[2ex] \dfrac{B_{j'} e^{+a_{\alpha j'} h_j}}{a_{\alpha j'}} \\[2ex] \dfrac{C_{j'} e^{-a_{\beta j'} h_j}}{a_{\beta j'}} \\[2ex] \dfrac{D_{j'} e^{a_{\beta j'} h_j}}{a_{\beta j'}} \end{bmatrix} \qquad \text{(11-b)}$$

One may express $\vec{A}_{j',j}$ as $\vec{A}_{j',j} = [A_{j',j}]\vec{A}_j$

where

$$[A_{j',j}] = \begin{bmatrix} e^{-a_{\alpha j'}h_j} & 0 & 0 & 0 \\ 0 & e^{a_{\alpha j'}h_j} & 0 & 0 \\ 0 & 0 & e^{-a_{\beta j'}h_j} & 0 \\ 0 & 0 & 0 & e^{a_{\beta j'}h_j} \end{bmatrix} \qquad (11\text{-c})$$

and

$$\vec{A}_{j'} = \begin{bmatrix} \dfrac{A_{j'}}{a_{\alpha j'}} \\ \dfrac{B_{j'}}{a_{\alpha j'}} \\ \dfrac{C_{j'}}{a_{\beta j'}} \\ \dfrac{D_{j'}}{a_{\beta j'}} \end{bmatrix} . \qquad (11\text{-d})$$

We now may write Eq. (10) as

$$[a_j][A_{j,j}]\vec{A}_j = [a_{j'}][A_{j',j}]\vec{A}_{j'} . \qquad (12)$$

Eq. (12) is a recurrence relation relating the coefficients of the j^{th} layer to the $j'=(j+1)^{th}$ layer. Solving for $\vec{A}_j$ gives

$$\vec{A}_j = [A_{j,j}]^{-1}[a_j]^{-1}[a_{j'}][A_{j',j}]\vec{A}_{j'} . \qquad (12\text{-a})$$

We may define

$$[b_{j',j}] = [A_{j,j}]^{-1}[a_j]^{-1}[a_{j'}][A_{j',j}], \qquad (12\text{-b})$$

which allows Eq. (12) to be written in a simpler form:

$$\vec{A}_j = [b_{(j+1),j}]\ \vec{A}_{(j+1)} . \qquad (12\text{-c})$$

One may apply the recurrence relation (12-c) successively to eliminate the coefficients of intermediate layers. In particular, one may express the coefficients of the first layer (j=1) to those of the last layer (j=n) as a product

$$\vec{A}_1 = \left\{ \prod_{\ell=1}^{n-1} [b_{(\ell+1),\ell}] \right\} \vec{A}_n , \qquad (13)$$

where we may set

$$[M] = \prod_{\ell=1}^{n-1} [b_{(\ell+1),\ell}] , \qquad (13\text{-a})$$

where [M] is a (4×4) matrix, so

$$\vec{A}_1 = [M]\ \vec{A}_n . \qquad (13\text{-b})$$

We recall that the second and fourth elements of $\vec{A}_n$ are zero due to a radiation condition. If one denotes the elements of [M] as m_{ik}, one may expand Eq. (13-b) as follows:

$$\begin{aligned} \frac{A_1}{a_{\alpha 1}} &= m_{11}\frac{A_n}{a_{\alpha m}} + m_{13}\frac{C_n}{a_{\beta n}} \\ \frac{B_1}{a_{\alpha 1}} &= m_{21}\frac{A_n}{a_{\alpha n}} + m_{23}\frac{C_n}{a_{\beta n}} \\ \frac{C_1}{a_{\beta 1}} &= m_{31}\frac{A_n}{a_{\alpha n}} + m_{33}\frac{C_n}{a_{\beta n}} \\ \frac{D_1}{a_{\beta 1}} &= m_{41}\frac{A_n}{a_{\alpha n}} + m_{43}\frac{C_n}{a_{\beta n}} . \end{aligned} \qquad (13\text{-c})$$

Eq. (13-c) relates the four coefficients of the first solid layer to the two coefficients of the last solid layer by means of the elements of the [M] matrix. The elements of the [M] matrix can be computed as a function of ζ knowing the densities and wave numbers of the viscoelastic layers.

Now one may relate the four coefficients of the first solid layer to the unknown coefficient A_0 [Eq. (6)] of the liquid layer by applying boundary conditions at the liquid-solid interface z=0. We write

$$\text{i)}\quad \sigma_{zz_0} = -p_0 = \sigma_{zz_1} \quad \text{at } z = 0 , \qquad (14\text{-a})$$

$$\text{ii)}\quad u_{z_0} = u_{z_1} \quad '' \qquad (14\text{-b})$$

$$\text{and}\quad \text{iii)}\quad \sigma_{rz_1} = 0 \quad '' \quad . \qquad (14\text{-c})$$

where p_0 is the liquid pressure given as $p_0 = -\rho_0\omega^2 G$ for $\vec{r} \neq \vec{r}'$. Using Eqs. (8) in (14) results in the matrix relation:

$$\begin{bmatrix} a_0\cosh\, a_0h_0 & a_{\alpha 1} & -a_{\alpha 1} & -\zeta^2 & -\zeta^2 \\ \rho_0\omega^2\sinh\, a_0h_0 & \rho_1\beta_1^2(2\zeta^2-k_{\beta 1}^2) & \rho_1\beta_1^2(2\zeta^2-k_{\beta 1}^2) & -2\rho_1\beta_1^2\zeta^2a_{\beta 1} & 2\rho_1\beta_1^2\zeta^2a_{\beta 1} \\ 0 & -2a_{\alpha 1} & 2a_{\alpha 1} & (2\zeta^2-k_{\beta 1}^2) & (2\zeta^2-k_{\beta 1}^2) \end{bmatrix} \times$$

$$\times \begin{bmatrix} \frac{A_0}{a_0} \\ \frac{A_1}{a_{\alpha 1}} \\ \frac{B_1}{a_{\alpha 1}} \\ \frac{C_1}{a_{\beta 1}} \\ \frac{D_1}{a_{\beta 1}} \end{bmatrix} = \frac{2}{a_0} \begin{bmatrix} a_0\cosh\, a_0z' \\ \rho_0\omega^2\sinh\, a_0z' \\ 0 \end{bmatrix} . \tag{15}$$

Applying the result (13-c) to Eq. (15) gives

$$\begin{bmatrix} a_0\cosh\, a_0h_0 & b_{12} & b_{13} \\ \rho_0\omega^2\sinh\, a_0h_0 & b_{22} & b_{23} \\ 0 & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} A_0/a_0 \\ A_n/a_{\alpha n} \\ C_n/a_{\alpha n} \end{bmatrix} = \frac{2}{a_0} \begin{bmatrix} a_0\cosh\, a_0z' \\ \rho_0\omega^2\sinh\, a_0z' \\ 0 \end{bmatrix} , \tag{16}$$

where

$$b_{11} = (m_{11}-m_{21})a_{\alpha 1} - \zeta^2(m_{31}+m_{41}) ,$$

$$b_{22} = \rho_1\beta_1^2(2\zeta^2-k_{\beta 1}^2)(m_{11}+m_{21}) -$$

$$- 2\rho_1\beta_1^2\zeta^2a_{\beta 1}(m_{31}-m_{41}) ,$$

$$b_{32} = -2a_{\alpha 1}(m_{11}-m_{21}) + (2\zeta^2-k_{\beta 1}^2)(m_{31}+m_{41}) ,$$

$$b_{13} = (m_{13}-m_{23})a_{\alpha 1} - \zeta^2(m_{33}+m_{43}) ,$$

$$b_{23} = \rho_1\beta_1^2(2\zeta^2-k_{\beta 1}^2)(m_{13}+m_{23}) -$$

$$- 2\rho_1\beta_1^2a_{\beta 1}(m_{33}-m_{43})$$

and $b_{33} = -2a_{\alpha 1}(m_{13}-m_{23}) + (2\zeta^2-k_{\beta 1}^2)(m_{33}+m_{43})$.

We may solve for A_0 from Eq. (16) using Cramer's rule

$$A_0 = \frac{2}{a_0}\frac{\Delta_1}{\Delta_0} , \tag{17}$$

where

$$\Delta_1 = K_1a_0\cosh(a_0z') - K_2\rho_0\omega^2\sinh(a_0z'), \tag{17-a}$$

$$\Delta_0 = K_1a_0\cosh(a_0h_0) - K_2\rho_0\omega^2\sinh(a_0h_0), \tag{17-b}$$

$$K_1 = b_{22}b_{33} - b_{32}b_{23} ,$$

and

$$K_2 = b_{12}b_{33} - b_{13}b_{32} .$$

Substituting the result (17) into the expression for the Green's function [Eq. (6)] yields

$$\underline{G}(\zeta,z,z') = \frac{2}{4\pi a_0}\sinh[a_0(h_0+z_>)] \times$$

$$\times\left\{\frac{K_1a_0\cosh(a_0z_<) - K_2\rho_0\omega^2\sinh(a_0z_<)}{K_1a_0\cosh(a_0h_0) - K_2\rho_0\omega^2\sinh(a_0h_0)}\right\}, \tag{18}$$

where $z_> = \mathrm{Max}(z,z')$ and $z_< = \mathrm{Min}(z,z')$. Using the symbolism $z_>$, $z_<$ combines the two expressions Eqs. (6-a and b) for $\underline{G}_>$ and $\underline{G}_<$ into one due to reciprocity. We note that the period equation is obtained by setting the denominator of Eq. (18) to zero, or from Eq. (17-b)

$$\Delta_0 = 0 .$$

The actual Green's function $G(r,z,z',\omega)$ is obtained by taking the inverse transform of Eq. (18) using Eq. (4-b)

$$G(r,z,z',\omega) = \int_0^\infty \underline{G}(\zeta,z,z',\omega)\; J_0(\zeta r)\zeta d\zeta . \tag{18-a}$$

Special Cases

1) One viscoelastic layer (n=1). Here we set in Eq. (13-c) $m_{11} = m_{33} = 1$ and the other $m_{ij} = 0$. The Green's function reduces to $\underline{G}(\zeta,z,z') =$

$$= \frac{2}{4\pi a_0} \sinh[a_0(h_0+z_>)] \left\{ \frac{\frac{\rho_1}{\rho_0} a_0[(2\zeta^2-k_{\beta 1}^2)^2-4a_{\alpha 1}a_{\beta 1}\zeta^2]\cosh(a_0z_<)-a_{\alpha 1}k_{\beta 1}^4\sinh(a_0z_<)}{\frac{\rho_1}{\rho_0} a_0[(2\zeta^2-k_{\beta 1}^2)^2-4a_{\alpha 1}a_{\beta 1}\zeta^2]\cosh(a_0h_0)-a_{\alpha 1}k_{\beta 1}^4\sinh(a_0h_0)} \right\} . \qquad (19)$$

Eq. (19) agrees, after taking the inverse transform, with Press and Ewing's(8) result for the liquid layer over a semi-infinite elastic solid [their Eqs. (26) and (27)]. Our result includes an extra $1/4\pi$ factor that results from the Green's function formalism, and the notation and sign conventions differ.

2) Infinite depth of liquid layer ($h_0 \to \infty$). In this case Eq. (18) reduces to:

$$\underline{G}(\zeta,z,z') = \frac{2}{4\pi a_0} e^{-(a_0z_>)} \left\{ \frac{K_1a_0\cosh(a_0z_<)-K_2\rho_0\omega^2\sinh(a_0z_<)}{(K_1a_0 - K_2\rho_0\omega^2)} \right\} . \qquad (20)$$

Here the frequency equation is simply

$$K_1a_0 - K_2\rho_0\omega^2 = 0 \quad . \qquad (20\text{-a})$$

3) Semi-infinite liquid over a viscoelastic halfspace ($h_0 \to \infty$, n=1). The Green's function reduces to:

$$\underline{G}(\zeta,z,z') = \frac{2}{4\pi a_0} e^{-(a_0z_>)} \left\{ \frac{\frac{\rho_1}{\rho_0} a_0[(2\zeta^2-k_{\beta 1}^2)^2 - 4a_{\alpha 1}a_{\beta 1}\zeta^2]\cosh(a_0z_<) + k_{\beta 1}^4a_{\alpha 1}\sinh(a_0z_<)}{\frac{\rho_1}{\rho_0} a_0[(2\zeta^2-k_{\beta 1}^2)^2 - 4a_{\alpha 1}a_{\beta 1}\zeta^2] + k_{\beta 1}^4a_{\alpha 1}} \right\} . \qquad (21)$$

This result is the same as Eq. (A-7) of the preceding paper(1), as would be expected.

Results and Conclusions

A general expression [Eq. (18)] is obtained, in transformed form, for the acoustic response due to a point source in a liquid layer overlying a multi-layered viscoelastic solid halfspace. Special cases of the result are presented [Eqs. (19), (20) and (21)] for one viscoelastic layer, infinite liquid depth and one viscoelastic layer combined with the infinite liquid depth.

To obtain the actual response, one must take the inverse transform of the expression [Eq. (18), or one of its special cases]. Taking the inverse transform requires evaluating a definite integral of the form indicated in Eq. (18-a). This integration was discussed(1) and approximate results (leading terms in an asymptotic expansion(9)) were obtained for the special case corresponding to Eq. (21).

The same techniques may be applied to Eq. (20) (the infinite liquid depth case), as the integrand is in the same form. The period equation [Eq. (20-a)] becomes more complicated due to the presence of solid layers between the two halfspaces. The solid layers (plates) produce a waveguide-like effect which manifests itself in a residue series, each term representing one mode of propagation. As pointed out by Jardetsky(2), only two branch line integrals will contribute to the response. These integrals correspond to the branch point singularities of the last viscoelastic layer ($a_{\alpha n} = 0$, $a_{\beta n} = 0$).

In the radiation zone, the steady-state plane-wave reflection coefficient may be obtained from Eq. (20) by expanding the sinh and cosh terms to yield the following:

$$\underline{G}(\zeta,z,z') = \frac{1}{4\pi a_0} \left[e^{-a_0(z_>-z_<)} + e^{-a_0(z_>+z_<)} \times \left\{ \frac{K_1a_0 + K_2\rho_0\omega^2}{K_1a_0 - K_2\rho_0\omega^2} \right\} \right] . \qquad (22)$$

The first term in Eq. (22) is the direct wave, as may be seen from Sommerfeld's(10) result. The second term represents the reflected wave. This follows from the leading term of a steepest descent integration of the inverse transform of the second term.(1) Following the development of Ref. (1) gives, for the plane-wave reflection coefficient:

$$\left[\frac{K_1a_0 + K_2\rho_0\omega^2}{K_1a_0 - K_2\rho_0\omega^2} \right]_{\zeta=\zeta_0} \qquad (22\text{-a})$$

where $\zeta_0 = k_0\sin\theta$, $\theta = \sin^{-1}(\frac{r}{R_I})$ is the angle of incidence, and $R_I = \sqrt{r^2+(z+z')^2}$. One notes that the reflection coefficient given in Eq. (22-a) is in a form similar to the usual impedance relation representing the reflection coefficient for two liquids

$$\frac{Z_1 - Z_0}{Z_1 + Z_0}$$

where $Z_0 = \rho_0 c_0$, $Z_1 = \rho_1 \alpha_1$.

For reasons discussed in Ref. (1), the primary interest in our research is in the special case corresponding to infinite water depth. The explicit calculation of the acoustic response for the two-layer case (n=2) using the methods of Ref. (1) is an ambitious undertaking due to the algebraic complexity. For three layers or more, direct calculations become unmanageable. For this reason, further development will be accomplished using machine calculations. That is, the integrand will be evaluated for arbitrary layers with the aid of the recurrence relation, and the subsequent integration will be done numerically. In addition, studies will be done separately to find the roots of the period equation [Eq. (20-a)].

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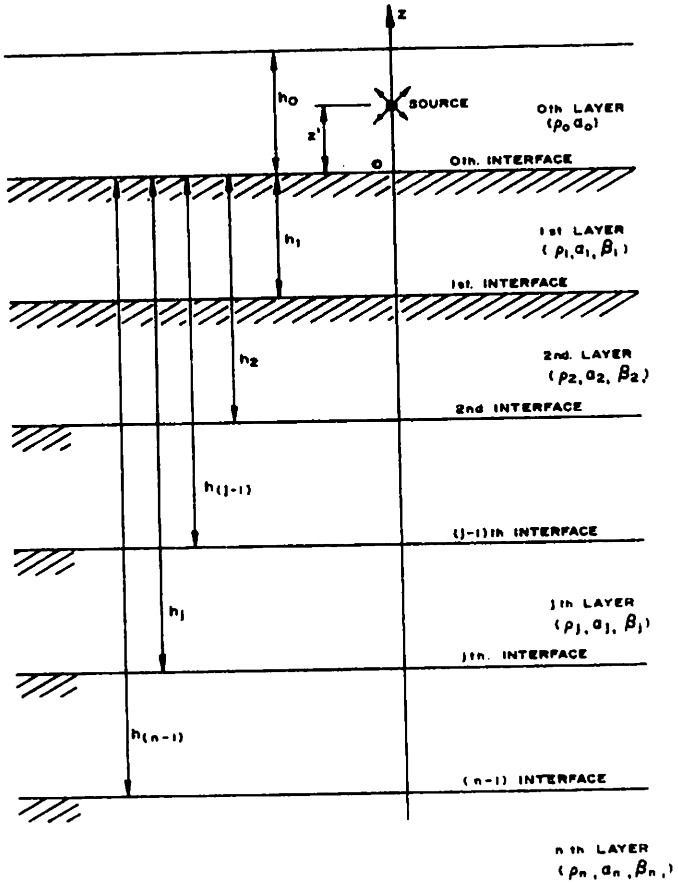

Figure 1. Dimensions and Coordinate System Used for Multi-layer Problem

APPENDIX III

Part C

A Summary of Project NOMES*

Introduction

The New England Offshore Mining Environmental Study (NOMES) is an experiment designed to monitor all aspects of the ocean environment - before, during, and after dredging - to evaluate the direct and indirect ecological effects of offshore sand and gravel mining. The major scientific objective of the experiment is to understand the effect sand and gravel dredging has on the marine ecosystem; thus, enabling us to predict the potential impact of marine mining operations. The experiment will provide a scientific basis for establishing realistic environmental safeguards over future mining operations.

Background

Sand and gravel provides, literally, the foundation on which the United States construction industry rests. Rebuilding cities, establishing rapid transit systems, and expanding our highway systems depend heavily on sand and gravel. Except for a few relatively small operations in bays, tidal rivers, estuaries, and large lakes, essentially all United States sand and gravel aggregate now comes from land-based operations. In 1971, aggregate

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* This summary has been taken, in part, from the Project Development Plan of the NOMES Project.

production from land-based operations in the United States was 987 million tons, valued at $1.2 billion. Over the past 20 years, production has increased an average of 5.5 percent per year. By 2000, the annual demand for sand and gravel will be three to four times what it now is. Furthermore, it is becoming increasingly difficult to maintain even today's rate of production at a reasonable cost. The onshore sand and gravel industry is experiencing a number of serious problems. Increasing demand coupled with depleting onshore land supplies, spiraling land prices, and increasing environmental constraints will seriously affect the industry unless other alternatives are developed. The United Kingdom has a flourishing marine sand and gravel industry that can deliver marine aggregate at dockside at costs equivalent to or less than those at land sites. In the United States where metropolitan areas, sufficient aggregate deposits, and navigable waters come together, offshore mining presents a feasible alternative. In at least four metropolitan areas - Boston, New York, Los Angeles, and San Francisco - these conditions exist and offshore sand and gravel operations could be pursued.

Unknowns regarding the environmental impact of offshore mining, however, have prevented such operations in the United States. These uncertainties have inspired legal and "de facto" moratoriums at all levels of government. The primary concerns are with the potential disturbance to fisheries ecology, coastal erosion, and degradation of recreational areas. Presently little is known about the nature and impact of offshore mining operations. A literature search by the Battelle Memorial Institute revealed that most environmental research has been limited to fresh and backrish waters. Silt from channel dredging and onshore placer mining as well as from natural runoff has considerably affected marine life. For several reasons, this research cannot be directly extrapolated offshore. Marine organisms in the ocean vary from those occuring in estuaries, lakes, and rivers; sediment types involved are not comparable in composition and organic content; tides and currents affect circulation to different degrees; and marine mining, as a continuous operation, may create more than a brief temporal change in the environment.

In the United Kingom, environmental monitoring and prediction studies have primarily centered on relationships between offshore sand and gravel mining and beach erosion. The United Kingdom has not conducted an integrated environmental study, although they have expressed interest in the results of the NOMES experiment.

Project NOMES grew out of the needs of both the Commonwealth of Massachusetts and those of the Federal Government for definitive information on the environmental impact of marine sand and gravel mining. Selection of the location for Project NOMES, in fact much of the impetus for the project, has resulted from the acute needs for sand and gravel in the east coast metropolitan areas of Massachusetts. Many of the land-based supplies near this area have been depleted; other potential reserves are inaccessible because of transportation problems or restrictive local earth removal ordinances.

Since 1968, there has been growing pressure in Massachusetts to allow marine aggregate mining for large projects such as the expansion of Boston's Logan Airport. However, fear that such operations would harm the Commonwealth's fishery resources led to a moratorium in 1971 that prohibits offshore mining until the ecological impact of such operations can be assessed.

Paralleling the Commonwealth interest, the Raytheon Company, the University of New Hampshire, and later the Massachusetts Institute of

Technology submitted proposals to the Office of Sea Grant to investigate the environmental effects of ocean dredging on marine life in Massachusetts Bay. The magnitude of the ecological study and the scope of the problems soon were rediscovered to be greater than originally envisioned; therefore, the Office of Sea Grant suggested that NOAA'a Marine Minerals Technology Center (MMTC) might play a constructive role in this endeavor.

One mission of the Marine Minerals Technology Center is to provide scientific advice about the effect of marine mining activities. In line with this responsibility, the Center is developing techniques to predict the ecological consequences of marine mining operations. Knowledge of the potential consequences will be a key factor in preparing leases, formulating regulations, establishing monitoring requirements, selecting sites, and modifying dredging equipment in an environmentally acceptable manner. This information is required by the Department of Interior, which is responsible for formulating offshore leasing regulations and by other Federal agencies in carrying out their duties.

Discussions between NOAA, the Commonwealth of Massachusetts, and other participating institutions led to an agreement that the needs of both Massachusetts and the Federal Government could be better satisfied by the pooling of abilities and resources in a joint experiment.

Technical Plan

Project NOMES will take place in Massachusetts Bay and require four and a half years to complete. The experiment will not answer all questions concerning the effect of sand and gravel mining on the environment; however, it will provide a general understanding of cause-and-effect relationships. Follow-up studies based on information gathered can be used to refine our understanding of these relationships and acquire further knowledge of the underlying mechanisms governing the influences of marine mining on the ecology.

The ecosystem involved in this experiment has four major elements: the seabed in the dredge site and silt impact area; the water column above it; marine life inhabiting both the water column and sea floor; and the atmosphere over the site. The dynamics of these subsystems are inextricably related.

Dredging operations will remove large quantities of sand, gravel and associated fine sediments from the mining site. The aggregate will be retained on-board the dredge while water-suspended fines are discharged overboard to form a silt plume downcurrent from the vessel. The sediments will gradually settle from the water column and impact the sea floor. The removal of the sand and gravel deposit may also affect the local sediment budget, and the excavated pit may change water patterns. Both may alter coastal erosion processes.

To describe and understand the environmental impact, various parameters will be monitored and sampled. Detailed plans are discussed later; the following discussion, however, illustrates the relationships between various facets of the experiment. To develop correlations between the deposit to be dredged and the potential environmental impact, the following must be accurately known:

Physical and chemical characteristics of the fine material in the deposit.

Dredge system characteristics.

Topography of the affected area.

Broad-scale, long-term water mass movements in the dredge site and impact areas.

Physical and chemical changes in the surrounding water mass.

Changes induced in various communities of marine life in the area.

Effects of changes in one biologic community or other communities in the food web.

Knowledge of these parameters is necessary to describe and understand the effects of dredging on the environment. Physical and chemical analyses of the fines are required to determine the amount and composition of the material the dredge system will put into the water column. Studies of currents are needed to delineate the location of the silt plume, so that sampling stations can be located appropriately. Water quality will be measured and compared with baseline data to determine changes induced in the water column. Topographical data are needed to correlate changes in sea floor configuration with alterations in wave refraction patterns and coastal erosion processes. Detailed biologic studies are required to document and understand the impact of dredging on marine life. To accomplish these objectives Project NOMES has been organized into four phases.

I. Pre-dredging dynamics environmental baseline
II. Dredging and monitoring
III. Postdredging monitoring
IV. Preparation of final and guidelines for regulatory agencies.

During the first three phases the seabed, water column, and biology of the dredge site and sediment impact area will be intensively monitored, and, where appropriate, laboratory studies will compliment the field test results.

<u>Phase I</u>: <u>Pre-dredging Environmental Baseline.</u> The objective of phase I will be to obtain a "before" picture of the geology, physical oceanography, and biology of the dredge site and impact areas; this data

will be correlated with postdredging findings. This phase will officially begin in February 1973; however, information collected in past studies of Massachusetts Bay and data gathered during the initial baseline selection and preparation period will contribute to this effort. The baseline study will continue until the spring plankton bloom in 1974, then dredging will commence.

Phase II: Dredging Operations and Monitoring. The dredge site is approximately 12 miles due east of Boston's Logan Airport in about 80 feet of water. Dredging operations will be initiated in 1974 at the beginning of the yearly biologic cycle, the spring plankton bloom, and will continue about two months. About one million cubic yards of material will be excavated. We expect that about 10,000 cubic yards will be fine sediments that, upon discharge, will have a definite, but as yet undefined, impact on marine life in the area. Monitoring of the geologic, physical oceanographic, and biologic parameters will be intensified during this phase of the experiment to determine the extent of the ecological disturbance.

Phase III. Postdredging Monitoring. This phase, lasting about 24 months, will collect data on any natural reestablishment of the affected biological communities and any physical restoration of the dredge pit. Additional studies will also determine if dredge induced changes in bottom topography or sediment budget affect natural coastal erosion processes.

Phase IV. Final Report Preparation. The last phase of this study will focus on interpreting the results and preparing the final report. Data collected during the first three field phases of this experiment, and complementary laboratory studies, will be evaluated and incorporated into models to help us understand the influence sand and gravel mining has on each biologic community. These individual models will then be integrated into an overall model encompassing the effects on the entire ecosystem. These models will also provide information on which properties should be monitored and evaluated during any continuous sand and gravel mining operations to determine its environmental impact.

APPENDIX IV

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(1971 - 1972)

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