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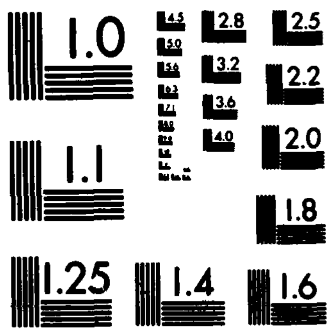

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ACOUSTICAL PROPERTIES OF LABORATORY AND IN SITU SEDIMENTS

FINAL REPORT UNDER CONTRACT N00014-76-C-0117

Paul J. Vidmar

APPLIED RESEARCH LABORATORIES
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3 October 1983

Final Report

1 August 1975 – 30 June 1983

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This report summarizes work done under Contract N00014-76-C-0117 during the period 1 August 1975 - 30 June 1983. Major accomplishments include: Development and use of instrumentation to perform in situ measurements of acoustical parameters of marine sediments, measurement of shear and compressional wave parameters of laboratory sediments, development of theoretical descriptions of acoustic propagation in sediments, and laboratory experiments to test various theoretical models of propagation in sediments.

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I. INTRODUCTION

Since January 1971, Applied Research Laboratories, The University of Texas at Austin (ARL:UT), has conducted ongoing research funded by the Office of Naval Research (ONR) to study the propagation of acoustical waves in ocean bottom sediments. The thrust of this research has been the study of acoustical properties of marine sediments by means of a coordinated program of measurements of sediment parameters coupled to theoretical efforts to understand and predict these parameters.

This report summarizes work carried out from 1 August 1975 to 30 June 1983 under Contract N00014-76-C-0117. A major part of the early efforts of the research program was the development of techniques and equipment to make accurate and inexpensive in situ acoustical measurements during routine geophysical coring. These have been successfully used in at-sea measurements. Another important product of the program was the development of a new type of transducer element for shear wave measurements in low rigidity media which makes possible both laboratory and in situ measurements of shear wave properties of unconsolidated sediments. A patent has been issued for this transducer. More recently the program has shifted away from an emphasis on in situ measurements and is now oriented toward a combination of laboratory measurements closely coupled to theoretical analysis. The ARL:UT program had as one of its objectives the development of competent researchers capable of pursuing careers in scientific and technological areas of interest to the Navy. This objective was achieved through continuing involvement of faculty and graduate students from The University of Texas at Austin. Publication of research results was also an important goal in the program. During its eight-year existence, a total of 35 reports, journal articles, and oral presentations have been produced, including 11 papers published in scientific journals. The Appendix is a cumulative listing of this documentation. The acoustics of marine sediments were and continue to be an important issue for a number of concurrent 6.1, 6.2, and 6.3 research projects at ARL:UT. Current 6.1 projects include: normal mode modeling of propagation in shallow water (ONR 425UA), nonlinear acoustics of sedimentary material (ONR 400R), and the relation between mechanical and acoustical properties of marine sediments (ONR 400R). In the 6.2 area, these include the bottom interaction (NAVELEX 612/NORDA 110A), high frequency (NAVSEA 63R/NORDA 110A), and mine-countermeasures (ONR Code 425AR) programs. In the 6.3 area, these include work sponsored by the SEAS (NORDA 530) and TAEAS (NORDA 530) programs, such as bottom loss upgrade (SEAS and TAEAS), measurement planning and analysis (SEAS), array characterization (SEAS), and broadband propagation (TAEAS). These projects not only identify gaps in basic research but are ready customers for results from the ONR 425GG program.

Section II of this report gives a brief review of work conducted during each year.

II. SYNOPSIS OF RESEARCH RESULTS

A. 1 August 1975 - 31 December 1976

During this period,[1] there were three major areas of research. First, the compressional wave profilometer was used on four major field trips with four different oceanographic institutions. A total of 66 sound speed profiles were made. The existing instrument was lost on the final field trip, so a new unit had to be constructed. Second, a method was developed to measure the acoustic impedance of a sediment by measuring the electrical impedance of a transducer in contact with the sediment. Laboratory work revealed that a linear relation exists between the electrical impedance and the acoustic impedance. The measurements were shown to be independent of temperatures below 30°C. Third, shear wave transducers were developed for use in deep ocean sediments, and prototypes were built. Laboratory measurements of attenuation were attempted on three sands at a wide range of frequencies; however, the scatter in the data resulting from reflections in the test tank obscured the frequency dependence.

B. 1 January - 31 December 1977

During 1977, research was carried out in three areas.[2]

(1) The existing compressional wave profilometer was used on one field trip to make in situ compressional wave measurements and to field test a preliminary design for an in situ shear wave transducer.

(2) Extensive development and laboratory testing was done on several in situ and laboratory type shear wave transducers and on an in situ acoustic impedance transducer.

(3) Laboratory measurements of shear wave and compressional wave speed and attenuation were made on laboratory sediments including sand, silt, and clay types.

In the first area, the ARL:UT compressional wave profilometer was used aboard USNS DESTEIGUER (AGOR-12) in conjunction with piston coring activities carried out by Naval Ocean Research and Development Activity (NORDA) personnel during cruise 13X3-77, leg 2. ARL:UT's primary objectives were to obtain compressional wave speed data, to test the new profilometer that had been constructed to replace the one lost in previous coring operations, and to test a new transducer configuration designed to measure both shear wave speed and compressional wave speed. Five cores were attempted with the profilometer attached, four cores were taken, and four sound speed profiles made; the first attempt failed due to pre-trigger of the corer. Laboratory sound speed data were measured on three of the cores through the plastic liner after retrieval of the cores on board ship.

Two of the in situ profiles were made in relatively soft material and exhibited a typical profile for this type material, showing an interface sound speed ratio less than one and a sound speed gradient greater than 1 sec^{-1}. In the case of the gradient, the value of 1.6 sec^{-1} was somewhat larger than the commonly accepted value of 1 sec^{-1}. The gradient was not measured in the laboratory profiles, which are uncorrected for temperature gradient and overburden pressure. This indicated that the mechanisms creating the gradient were released once the core becomes isothermal and isobaric.

The last two cores were made in stiff sand overlaid by a thin mud layer. Accurate sound speeds were only obtained in the mud layer except for the high sound speed observed once the corer came to rest. The accuracy of this latter sound speed measurement was questionable due to the expected large disturbance to the sediment from the hard impact in the sand.

The ARL:UT profilometer was shown to be a valuable tool for the measurement of ocean bottom acoustic parameters. The above measurements were made at little expense and relatively little additional effort as an adjunct to a routine coring exercise. A comparison between the in situ and laboratory profiles showed the value of obtaining acoustic data in situ since the laboratory profile rapidly changes with time and does not retain information about sound speed gradient. Of course, the laboratory data could be corrected for temperature gradient and overburden pressure, but these data in themselves must either be measured or assumed.

In the second area, ARL:UT continued to develop the technology required to make shear wave and acoustic impedance measurements in situ. As a result of the in situ transducer development, more sensitive laboratory transducers for shear wave measurements were also produced. Transducers for measuring the shear wave parameters of typical marine sediments were designed and constructed. Preliminary testing identified problems with early designs. Indicated changes were made and the transducers were tested both in the laboratory and in situ. Additional shear wave transducers that exhibit greater sensitivity and bandwidth than comparable in situ types were designed for use in the laboratory. Transducers for measurement of acoustic impedance in situ were designed and evaluation begun.

In the third area, accurate shear wave measurements were made in unconsolidated sediments. These measurements, which used single bender elements developed at ARL:UT as both source and receiver, were relatively easy to make, and it was envisioned that shear wave measurements could be made routinely to compliment the large volume of compressional wave data in the literature. The results of these measurements indicated, however, that the amount of disturbance created during measurement is critical. In general, the measurements produced expected results, but improvements in experimental procedures were still needed to measure the frequency dependence of the shear wave speed and attenuation and to determine the porosity. Several improvements in experimental technique were identified, including the use of uniformly sized and shaped glass spheres which would allow better handling of such variables as grain size and porosity.

C. 1 January - 31 December 1978

During 1978, research[3] was conducted in four major areas: (1) the profilometer equipment was used in the field to make compressional wave measurements in situ and to test shear wave transducer design, (2) a method was examined for calculating sediment shear strength from in situ deceleration profiles for the corer, (3) design and development of in situ shear wave and acoustic impedance transducers was continued to maximize sensitivity and ruggedness, (4) theoretical and experimental research continued to develop models for acoustic propagation in sediments.

In the first area, field tests were conducted aboard ship in the deep ocean environment. The purpose of this trip was to record in situ compressional wave velocity profiles by using the profilometer attached to a modified large piston corer. Newly designed shear wave transducers were also to be tested during this trip. The first core was taken without the profilometer attached so that operation and timing of the coring system could be observed. For the second test, the profilometer, including the new shear wave transducers, was attached. During retrieval of the second corer, the coring cable parted, causing the loss of both the corer and the profilometer. As a result, no data were obtained and the new shear wave transducer design remained untested. Because this was the last remaining profilometer recorder, two new recording units had to be built for use in 1979. The system was redesigned to incorporate improved electronic circuitry to reduce power consumption and to extend the capability of the profilometer to concurrently measure compressional wave, shear wave, and acoustic impedance parameters.

In the second area, ARL:UT explored the feasibility of using the deceleration of the corer, which is recorded on one of the data channels of the acoustic profilometer, to measure the in situ shear strength of the ocean floor. The acceleration history during penetration was normally used to develop a depth axis to plot the sound velocity profile. The potential for using these data to obtain a measurement of the static shear strength of the sediment was tested using three archived data sets. It was found that the gradient in shear strength measured with the accelerometer records was much less than that measured by conventional means. Several causes for the discrepancies were identified which reduce the value of the accelerometer based measurement.

In the third area, the newly constructed profilometers used new shear wave transducers redesigned to improve their durability. The shear wave bender elements were shortened so that the pressure compensating chamber could be placed at the back of the housing. This resulted in a more monolithic structure that is less subject to abuse. Work was also done to develop new acoustic impedance transducers capable of stable operation at great depths with a minimum change in operating characteristics. This transducer was under test in a variety of liquids.

In the fourth area, laboratory measurements were made in a number of natural and artificial sediments. This research concentrated on the shear wave properties of the various sediment samples since past research had been dominated by studies of compressional wave propagation. It was also recognized that shear wave measurements could be made in the laboratory over a range of frequencies where viscous effects should be most evident. This region has been neglected in compressional wave laboratory studies because of experimental difficulties caused by long wavelengths. The general agreement of the shear wave results with predictions of a viscous loss model, although not conclusive, implied that the available compressional wave data should be carefully reassessed.

Control of extraneous stresses that influence the rigidity of the sediment is an important aspect of the ARL:UT laboratory program of shear wave measurement. Both the finite size of the test chamber and the method of compaction can influence the packing of sand sized particles. The 150 liter sediment tank used in the present study is a convenient size for laboratory measurements in sand. There is sufficient sediment mass to reduce the influence of minor vibrations on the packing, and yet the mass is not too large to easily vibrate to reach minimum porosity. The tank is also small enough to allow deaeration of the entire sediment. An irregular porous foam liner was found to be an efficient absorber of shear wave energy. This allowed interference from reflections to be minimized.

High quality shear wave signals were generated and detected by bender elements. The broadband characteristics of the transducers allowed velocities and attenuations to be measured over more than a decade of frequency. Data in a natural sand and an artificial sediment made of glass beads indicated that dispersion, if present, was less than approximately 5% between 0.5 and 20 kHz for both dry and saturated specimens. The shear wave velocity decreased with water saturation. The frequency dependence of the attenuation could be adequately approximated as proportional to the first power of the frequency over the range of the experiments.

Two techniques were investigated for measuring the nonlinearity parameters of saturated marine sediments. The first depended upon measuring the radiation impedance of a piston transducer as a function of particle velocity or driving power. The second method involved measurement of the propagation of nonlinearly generated second harmonic signals. The accuracy and feasibility of the two methods were compared. The harmonic generation method was potentially more accurate but the impedance method avoided problems associated with the geometry of propagation.

D. <u>1 January - 31 December 1979</u>

During 1979, the ARL:UT sediment acoustics program progressed[4] in three areas.

(1) Three field trips were made, two successfully completed, on which five in situ compressional wave speed profiles were made, adding to the growing base of in situ wave data for various areas of the world. Four profiles were made in the Gulf of Mexico and one in the Caribbean Sea.

(2) A test using a shear wave transducer to obtain an in situ shear speed profile was accomplished. Although the data were not as good as analogous compressional wave data, it showed that such data could be obtained.

(3) Analytical models using only easily measured physical parameters were developed for compressional wave propagation in porous media (such as sands). These models were based on those of Biot and Stoll, with some extension to fine grain clay type sediments. Model predictions were compared to laboratory data and showed good agreement. Studies of temperature effects on shear wave and compressional wave propagation in sands and clays were successfully carried out and showed that previously unsubstantiated assumptions about temperature dependence were essentially correct.

E. <u>1 January - 31 December 1980</u>

During 1980, the ARL:UT sediment acoustics program was involved in two areas of work.[5]

(1) The in situ acoustic measuring system was reconfigured to enable concurrent measurement of compressional wave velocity and attenuation, shear wave velocity and attenuation, and

acoustic impedance. The recording instrument and transducers were successfully tested in the laboratory and were prepared for extensive field testing.

(2) A laboratory experiment was concluded to test predictions of the analytical model of acoustic propagation in sediments developed the previous year. Viscosity of the pore fluid in an artificial sediment of spherical glass beads was varied by mixing various concentrations of glycerin with water. Results of the experiment indicated that predictions of the model do not match measured data. Further examination and modification of the model, plus repeat of the measurements, were indicated.

F. 1 January - 31 December 1981

During 1981, the ARL:UT sediment acoustics program began to phase out the development of the in situ profilometer and to concentrate on theoretical and laboratory experimental research and the acoustic properties of marine sediments.[6] New faculty and students from The University of Texas at Austin became involved in the program. The major effort was to continue laboratory measurements, begun in 1980, on artificial sediments with different mixtures of glycerol and water as a pore fluid. The data were analyzed and the measurements repeated to clarify some points with more refined experimental techniques. The new data were more consistent with the theoretical predictions. However, the new data still exhibited anomalous features which did not agree with the theory; further investigation was required.

G. 1 January - 30 June 1983

In 1982, the ARL:UT program worked in three areas,[7] each of which produced tangible results in terms of either journal publications or reports. The first area was theoretical analyses of two subjects: (1) propagation in sediments containing gas bubbles and (2) the comparison of Biot and viscoelastic treatments of reflection from sedimentary material. A journal article on the first subject was published, while work on the second continued. The second major research area was an experimental program to verify various aspects of the Biot approach to propagation in marine sediments. In particular, the dependence of shear and compressional velocities and absorptions on viscosity was measured and compared to theoretical predictions. Preliminary results of these measurements were submitted for journal publication. The third major area was the design of an experiment to measure the acoustical properties of hydrated marine sediments. The design was completed and described in a report.

In the first area, research was performed to model a gassy sediment as a three-constituent mixture: solid, liquid, and gas. A variational method of deriving equations of motion for mixtures is used to obtain a theory for a granular sediment saturated by a liquid which contains bubbles of gas. The theory is an extension of the Biot approach to wave propagation in saturated sediments. Wave velocity and attenuation were determined for a water-saturated model sediment containing a small volume of air bubbles. The model predicted the qualitative features that had been observed experimentally in gassy sediments. Work was also begun to apply the Biot-Stoll approach to describing reflection from a depth dependent sea floor. A preliminary study of this problem was carried out. Consideration was given to several techniques for including depth dependence of the material parameters, including taking an integral transform in the depth coordinate or treating the sediment as a layered medium. The approach that was favored was to numerically integrate the governing equations in the depth direction, assuming a layer of sediment material to overlay an elastic substrate. A computer code has been written and will be used to compare the results of the Biot-Stoll approach to the traditional viscoelastic approach.

In the second area, further work was done to refine the experimental procedures in preparation for a third set of measurements to resolve discrepancies between the first two. Measurements of the radiation pattern of the transducers and alternate electronic configurations were examined.

In the third area, ARL:UT designed an experimental apparatus and developed an experimental plan to measure the acoustical behavior of marine sediments bearing gas hydrates. Hydrates are icelike crystalline structures that can significantly alter geoacoustic parameters such as shear and compressional velocities and absorption. The acoustic behavior of hydrated marine sediment can differ greatly from that of nonhydrated sedimentary sequences. Recent calculations indicate that bottom loss from hydrated marine sediments is particularly sensitive to the as yet unknown values for shear velocities. Potentially favorable conditions for the formation of hydrate zones exist over 90% of the ocean floor and to a considerable depth in the sediment. The goal of the experimentation is to obtain values for shear and compressional velocities in a variety of hydrated sediments. The apparatus consists of an acrylic vessel designed to contain sediments and gases under sufficient pressure-temperature conditions to form gas hydrates. Xenon gas will be used initially to form the structure I hydrate, followed by the use of propane gas which forms the structure II hydrate. Both of these structures occur in marine sediments. The low dissociation pressures of xenon hydrates (1.5 atm) and propane hydrates (1.74 atm) will enable a safe and efficient performance in the laboratory environment. The vessel is designed for installation of instrumentation capable of measuring the acoustical, thermal, and electrical properties of gas hydrates in sediments.

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APPENDIX

CUMULATIVE DOCUMENTATION
ARL:UT SEDIMENT ACOUSTICS PROGRAM
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Contract N00014-76-C-0117

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