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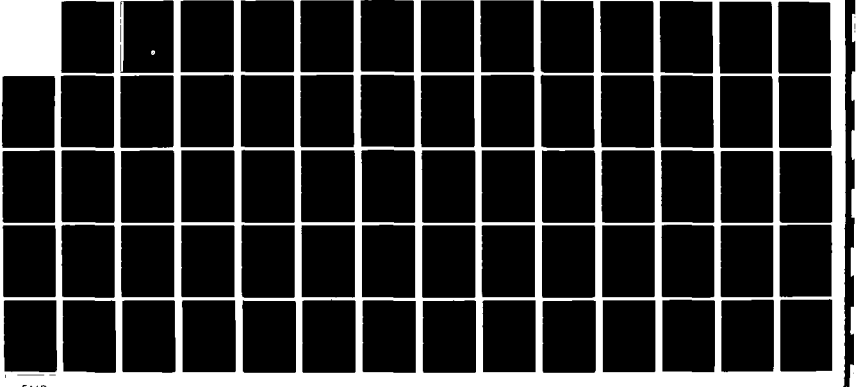

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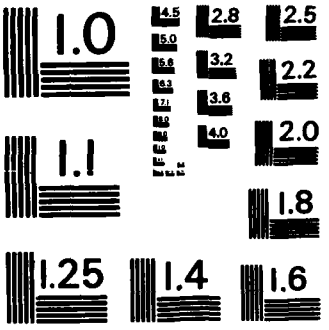

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ACOUSTICAL PROPERTIES OF SEDIMENTS

Annual Report under Contract N00014-76-C-0117

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Glen E. Ellis
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During 1981, work under Contract N00014-76-C-0117 included laboratory measurements and theoretical analysis of the acoustic properties of saturated sediments. In this report, measurements and analysis of the acoustics of coarse sediments with a varied pore fluid are presented. It was found that measurements of compressional and shear wave velocities generally conform to predictions of the Biot-Stoll theory. These results came after a modification →

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of procedures to permit fluid variation without disturbing the sediment pack. This report also presents a short discussion of sediment issues as they relate to low frequency ocean acoustics.

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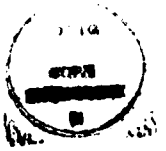

LIST OF FIGURES

I. INTRODUCTION

Since 1972, Applied Research Laboratories, The University of Texas at Austin (ARL:UT), has been heavily involved in research and development in low frequency ocean acoustics for the U.S. Navy. Most of this work has been exploratory and advanced development. It has included development of numerical modeling for both research and applications; i.e., planning, collection, and analysis of planned and existing acoustic systems. One aspect of this ARL:UT effort is that it exposes questions which are appropriate to basic research, and for which answers will find ready applications.

Part of the overall propagation studies at ARL:UT is a basic research program funded by Office of Naval Research (Code 425) devoted to measurement and modeling of acoustical properties of ocean sediments. The research program originated as an effort to measure acoustical parameters of sediments in situ during coring operations. An instrument called a profilometer, described in many of the references contained in Appendix B, was developed to measure compressional wave velocity, shear wave velocity, and impedance profiles. Use of the profilometer requires only minor changes to the cutter head of a geophysical corer; it has been used on several cruises.

During the development of the profilometer, it was necessary to improve the sensitivity and size of acoustic transducers. In particular, this work provided a significant improvement in shear wave transducer sensitivity; a patent was issued for this design. These transducer improvements proved to be just as useful for basic laboratory measurements as for field work. Thus, part of this program began to include laboratory work with carefully controlled sediments, and theoretical analytical work as part of the interpretation of those measurements.

During 1981, the program began to discontinue development of the in situ profilometer and to concentrate on theoretical analysis and laboratory measurements. To bolster the theoretical effort, faculty and students of the Department of Aerospace Engineering and Engineering Mechanics of The University of Texas at Austin, who specialize in the study of mechanical properties of composite materials, are participating in this program on a regular basis.

During 1980, laboratory measurements were begun on artificial (glass bead) sediments with different mixtures of glycerol and water as a pore fluid. During 1981, these results were analyzed and prepared for publication (Appendix A of this report contains a preprint of this publication). Then, to clarify some points which arose during that analysis, measurement techniques were modified and the experiment was repeated. Those results are included in Section III of this report.

A bibliography of publications under the sediment acoustics program is included as Appendix B. Since the program was started, 15 technical reports have been published, 14 papers have been presented at technical meetings, eight papers have been published in or presented to scientific journals, three papers have been included in books, and two invention disclosures have been submitted for patent. Of these, in 1981 one technical report was issued, one publication submitted, and one technical presentation given.

II. SEDIMENT ACOUSTICS ISSUES IN LOW FREQUENCY SOUND PROPAGATION IN THE OCEAN

A. Low Frequency Propagation and the Seabottom

As mentioned in the introduction, ARL:UT is involved in several areas of low frequency ocean acoustics. This exposure has pointed out several issues which we feel will be supported at a basic level by the research under this program. In this section, we first briefly identify some of these problems. Then we discuss some of the issues related to theoretical analysis of the acoustical properties of sediments.

Studies of low frequency (25-1000 Hz) ocean acoustics are usually divided between deep ocean regions (depths of 2000 m or more) and shallow water regions (depths of 2000 m and less). Usually, depths of 500-2000 m are continental slopes and are thus localized; for that reason, 500 m is a practical maximum depth for shallow water. A general study[1] of the bottom acoustics issues for exploratory development work has recently been prepared by Naval Ocean Research and Development Activity (NORDA) Code 530; it goes into some detail about acoustical mechanisms and their relationship to Navy acoustical systems.

For deep water propagation, the quantity of most interest is the loss of energy per bottom interaction, i.e., per refraction in, or reflection from, the bottom. That quantity has in the past been characterized as "bottom loss." However, the more sophisticated current applications model the bottom as part of the propagation medium, and thus require an understanding of bottom acoustics. Deep ocean sediments, with small grain sizes and soft compositions, are readily penetrated by sound. Examining typical velocity gradient and attenuation values, one can deduce that the properties of sediments at 200-500 m depth are important at 50 Hz. At 200 Hz, depths greater than

100 m are usually not important since sound penetrating more deeply will be very strongly attenuated. Routine coring to these depths cannot be done, so acoustical (or seismological) probes are an essential part of sediment measurements.

There are two general deep water acoustic propagation issues for this program. First, the physical mechanism of sound attenuation in sediments needs to be established by laboratory measurements and analytical work. This effort will strengthen present capabilities to interpret and extrapolate acoustical measurements made at sea, in both region and frequency. A second and distinct issue is the presence of gas hydrates in marine sediments. The survey paper by Daniels and Vidmar[2] reviews what is known about these formations, which apparently are common in the ocean, with particular attention to their acoustical implications.

In shallow water, acoustic bottom interaction is a more dominant factor than it is in deep water. That is due to the fact that except in isothermal water such as in the Arctic, shallow water sound repeatedly interacts with the bottom. However, the depth scales of interest have changed relative to deep water. The work of Mitchell and Focke,[3] for example, shows that in shallow water the bottom properties are important at 50 Hz to 50 m of sediment, while only a few meters are important at several hundred hertz. Thus, the sediment properties important to low frequency acoustic propagation may potentially be directly determined by coring.

As with the deep water case, an important shallow water acoustic propagation issue is the interpretation and extrapolation of bottom acoustical measurements. In addition, shallow water is more likely to contain coarsely grained sand for which some predictions of the Biot-Stoll theory can be consequential. Thus, extension of that theory to real (variable grain size, shape, and composition) is important.

B. Comments on the Status of Theoretical Modeling of Acoustic Waves in Saturated Sediments

An important part of the analysis of acoustic waves in the ocean is the prediction of wave interactions with the bottom. This is a most complex problem, not only because of the irregular topography and the inhomogeneity of the ocean bottom, but because the material comprising the bottom is a fluid saturated porous material having very complicated mechanical characteristics.

In this section, a summary is given of the theoretical models which have been developed for the analysis of wave propagation in saturated sediments. First, theories for wave propagation in the unbounded medium are considered. The single component approach is treated briefly, followed by a more extensive discussion of the mixture theory, due to Biot. Next, some recent progress on the reflection and refraction of waves at a plane interface between the water and a water saturated sediment is described.

The simplest approach to analyzing waves in saturated sediments is to model the saturated sediment as a single continuous medium. The mechanical properties of a continuous medium are chosen so that its behavior is equivalent, in a necessarily limited sense, to that of the saturated sediment. Since waves in saturated sediments in general exhibit dispersion and attenuation, the equivalent continuous medium must be viscoelastic.

Models of this type have been discussed by Hamilton.[4-8] He suggests the use of the particularly simple linearly viscoelastic model in which the Lamé constants λ and μ of an isotropic, linearly elastic material are replaced by complex moduli $\lambda+i\lambda'$, $\mu+i\mu'$. The moduli λ, λ', μ, and μ' are assumed to be frequency dependent and are to be determined from experiment. This type of model is equivalent to a Voigt material.[9] Hamilton cites developments of the model by Ferry[10] and White.[11]

Such a purely empirical approach has substantial advantages and disadvantages. The primary advantage is its simplicity. Once the coefficients in the theory have been evaluated as functions of frequency, then the large body of literature and many existing computer programs on wave propagation in viscoelastic materials can be used to obtain solutions to specific problems. On the other hand, since the model does not explicitly incorporate the physical properties of the saturated sediment, the coefficients in the theory must be measured anew for each change in the properties of the material. More importantly, the theory does not have the ability to predict the effects on wave propagation of changes in the material properties.

In order to introduce the physical properties of the saturated sediment, the material can be modeled as a binary mixture of fluid and solid constituents. By retaining the individual identities of the fluid and solid, it is possible to express at least part of the coefficients in terms of the physical properties of the two constituents.

A theory of this type was developed for application to fluid saturated, porous elastic media by Biot.[12-15] While he derived his equations on a somewhat intuitive basis, many subsequent studies have confirmed that they are consistent with the principles of continuum mechanics (see, for example, Bowen,[16] and Bedford and Drumheller[17]).

Biot's equations can be written

$$(1-\phi)\,\rho_s\,\ddot{u}_{(s)m} = -m\left[\ddot{u}_{(s)m}-\ddot{u}_{(f)m}\right] + A\,e_{(s)kk,m} + 2\mu_b\,e_{(s)mk,k} + Q\,e_{(f)kk,m} - b\left[\dot{u}_{(s)m}-\dot{u}_{(f)m}\right] \quad , \quad (1)$$

$$\phi\rho_f\,\ddot{u}_{(f)m} = m\left[\ddot{u}_{(s)m}-\ddot{u}_{(f)m}\right] + Q\,e_{(s)kk,m} + R\,e_{(v)kk,m} + b\left[\dot{u}_{(s)m}-\dot{u}_{(f)m}\right] \quad , \quad (2)$$

where ϕ is the porosity, ρ_s and ρ_f are the mass densities of the solid and fluid, $u_{(s)m}$ and $u_{(f)m}$ are the displacement vectors of the solid and fluid, the notation ,m denotes partial differentiation with respect to the coordinate x_m, $e_{(s)mk}$, and $e_{(f)mk}$ are the linear strains of the solid and fluid $e_{(s)mk}=1/2\left[u_{(s)m,k}+u_{(s)k,m}\right]$, and A, μ_b, Q, r, c, and b are constitutive coefficients.

Equations (1) and (2) are the equations of motion for the solid and fluid constituents, respectively. The first term on the right of each equation is a virtual mass term which is linear in the relative acceleration of the constituents. The last term on the right is a drag term which is linear in the relative velocity of the constituents. By using the solution for an oscillating cylinder containing a viscous fluid, Biot was able to evaluate the coefficient of the drag term b as a function of frequency.[13]

In a further important development, Biot and Willis[18] showed that the coefficients A, Q, and R could be expressed in terms of the bulk modulus of the solid material, the bulk modulus of the fluid, and the bulk and shear moduli of the drained porous solid K_b and μ_b.

The Biot theory was first applied to marine sediments by Stoll and Bryan[19] and Stoll.[20-22] In order to account for dissipative effects associated with motion of the granular matrix material, these authors assumed that the moduli K_b and μ_b were viscoelastic. Based upon experimental data on dry granular media, it was assumed that K_b and μ_b were complex constants. It was shown by Stoll that the theory could correctly predict the variation with frequency of the attenuation of compressional waves in saturated sands.[20]

The work of Stoll and Bryan was extended by Hovem and Ingram,[23] who showed that Biot's technique for evaluating the drag coefficient b could be used to evaluate the virtual mass coefficient c as well. They were also able to obtain a more explicit expression for b in the case of a sediment consisting of particles of uniform size. They then presented

very favorable comparisons of the theory with measurements of compressional wave attenuation in saturated sands. In addition, they presented new experimental data on compressional waves in a model sediment consisting of spherical glass beads saturated by water and showed that the theory correctly predicted both the attenuation and phase velocity of compressional waves.

Thus, the extended Biot theory has been shown to give quite accurate predictions in comparisons with direct measurements of both phase velocity and attenuation in saturated sediments.

Stoll[20] has used the Biot theory to show that the dominant loss mechanism at high frequencies is the drag between the solid and fluid constituents, while the dominant mechanism at low frequencies is dissipation in the viscoelastic granular matrix.

Because the scale of measurements of phase velocity and attenuation is necessarily small in a laboratory setting, the data are in the kilohertz frequency range and above. Such measurements cannot be used to verify the theory at lower frequencies. Stoll[24] has obtained some low frequency data on the attenuation of shear waves in saturated sediments by using a resonant column technique, but he gave only qualitative comparisons with the theory.

There is a pressing need for additional data at low frequencies and for data which can shed light on the viscoelastic properties of the granular matrix.

Recently, Shirley et al.[25] presented direct measurements of phase velocity and attenuation in a glass bead sediment saturated by a mixture of water and glycerol. By varying the proportion of glycerol, the viscosity of the liquid could be changed. In comparison with the extended Biot theory, the data predicted a substantially greater increase in attenuation with increasing viscosity. The measurements were made at a single frequency. Measurements made for a range of frequencies would greatly aid in characterizing the viscoelastic

response of the granular matrix. This, in turn, could conceivably permit extrapolation of the theory to low frequency.

The ultimate objective of efforts to model wave propagation in saturated sediments is the analysis of wave interactions with the ocean bottom. Although much work remains to be done on propagation in the unbounded medium, important progress on the interaction problem has recently been made by Stoll and Kan.[26] They considered a liquid half-space above a half-space of saturated sediment, and solved the problem of the reflection and refraction of the plane waves at the interface using the extended Biot theory. The analysis was based on the earlier work on saturated porous media by Deresiewicz and Rice.[27]

In contrast to the results for elastic media, they showed that the reflection coefficient exhibited strong frequency dependence, and was also a function of the assumed value of permeability of the sediment. The results obviously have important implications for the modeling of bottom interactions.

The analysis of Stoll and Kan will have to be extended before realistic estimates of bottom loss can be achieved. They assumed that the sediment properties were homogeneous and isotropic. It is, of course, well known that sediment properties are strongly depth dependent.[8,22] There is also some evidence that sediments are anisotropic.[28,29] Both of these factors would influence the reflection and refraction of waves.

III. NEW LABORATORY MEASUREMENTS OF WAVE PROPAGATION DEPENDENCE UPON PORE FLUID PROPERTIES

One set of measurements of the acoustic properties of a glass bead sediment with varied fluid makeup was taken in 1980.[30] This work was analyzed and prepared for publication in 1981; a preprint is contained in Appendix A of this report. The measurements were of compressional wave and shear wave velocities and attenuations in a sediment with a pore fluid. The content of the fluid was varied from pure water to 28% glycerol in water. (The terms glycerol and glycerine are both used to designate the compound $C_3H_8O_3$; the former is preferred in the chemistry literature.) It was found that the velocity measurements generally conformed to the predictions of the Biot-Stoll theory. However, the attenuation data were more scattered, and approximately doubled with a change from 0% to 28% glycerol. This was in contrast to calculated theoretical changes of attenuations, which amounted to only a few percent. Thus, it was decided to repeat the measurements and try to minimize sediment disturbance. Signal levels, the measured quantities which are converted to attenuation, are most sensitive to sediment disturbance.

A. Physical Properties

Variations in the viscosity, density, and bulk modulus of the aqueous solution were determined experimentally, and are shown in Figs. 1 and 2 as a function of the percent concentration of glycerol by weight in the solution. The viscosity and density properties were checked against published data for accuracy.

The viscosity η (Poise) was measured at 23^{o} with an Ostwalt viscometer, and the density ρ_f (g/cm^3) with a calibrated 100 ml

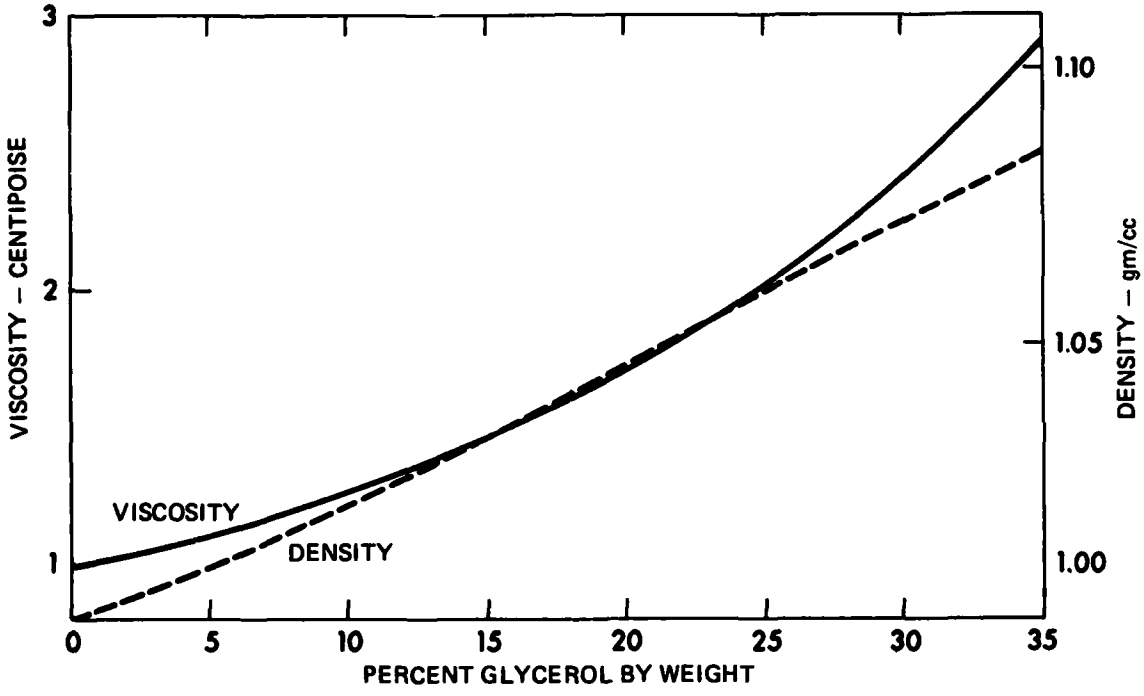

FIGURE 1
DENSITY AND VISCOSITY versus PERCENT WEIGHT OF GLYCEROL IN SOLUTION

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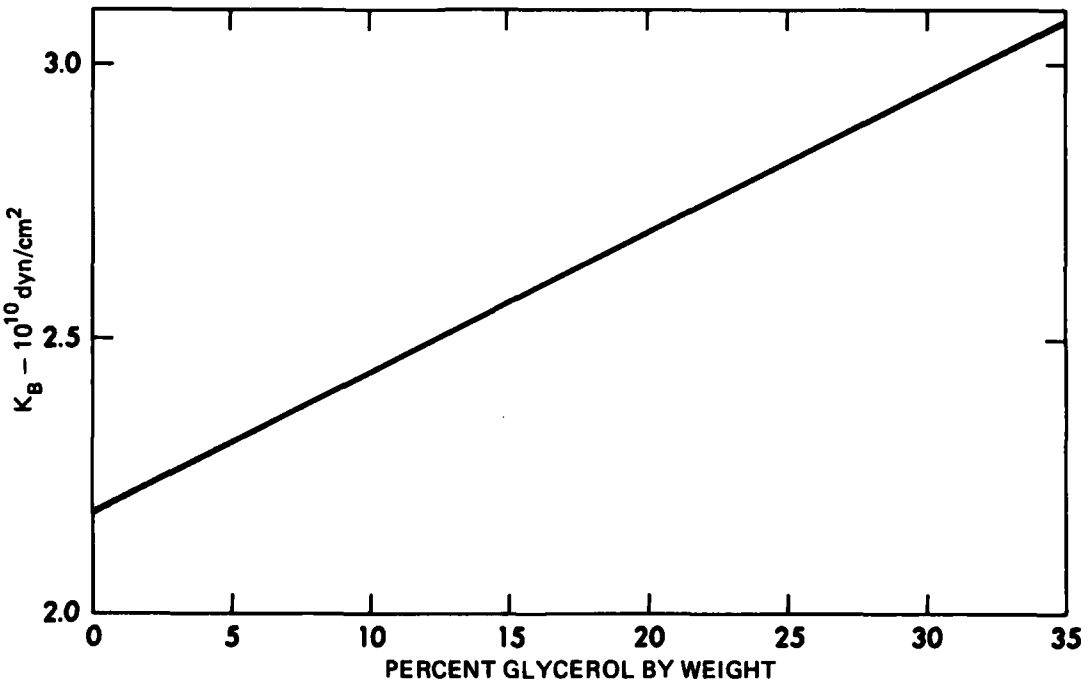

FIGURE 2
BULK MODULUS versus PERCENT WEIGHT OF GLYCEROL IN SOLUTION

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picnometer. The bulk modulus K_f (dyn/cm^2) was determined by measuring the compressional wave velocity and attenuation in a solution containing various concentrations of glycerol, then using this data in conjunction with the data on density to compute the bulk modulus of the solution.

The physical data that constitutes the characteristics of the glass beads are shown in Table I and were supplied by the manufacturer of the beads. A different size of beads than was used in the work of Appendix A was selected.

B. Preparation of the Sediment

The sediment was prepared in a steel tank (16 cm x 30.5 cm x 20 cm deep) by adding deionized water to initially dry glass beads, occupying 85% of the tank's volume, until the water exceeded the top surface of the beams by 1 cm. During this procedure, air bubbles are always entrapped in the beads. To remove this air, the tank was subjected to a vacuum for 24 hours and then heated to boiling, for about one hour. The tank was then allowed to cool to room temperature (approximately 23^{o}C) and then stirred with a slender rod to visually inspect for any air bubbles rising to the water's surface. After all trapped air was removed, the tank then became one part of a fluid circulating system. This apparatus, shown schematically in Fig. 3, facilitated the variation of the glycerol concentration without disturbing the sediment. The acoustic transducers were embedded in the sediment to a depth of approximately 8 cm, and then the apparatus remained undisturbed for at least 24 hours. The transducers that were used for acoustical measurements were similar to those used for the work described in Appendix A, and consisted of a shear wave bender element mounted so that the plane of the bender was vertical. A small compressional wave element was near the bender element. Compressional wave data were measured at a frequency of 114 kHz and shear wave data were measured at 2.8 kHz.

TABLE I

PHYSICAL CHARACTERISTICS OF SPHERICAL GLASS BEADS OF SEDIMENT

Diameter	0.0707 cm
Density	2.5 gm/cm^3
Bulk modulus	3.5×10^{11} dyn/cm^2
Porosity	0.373

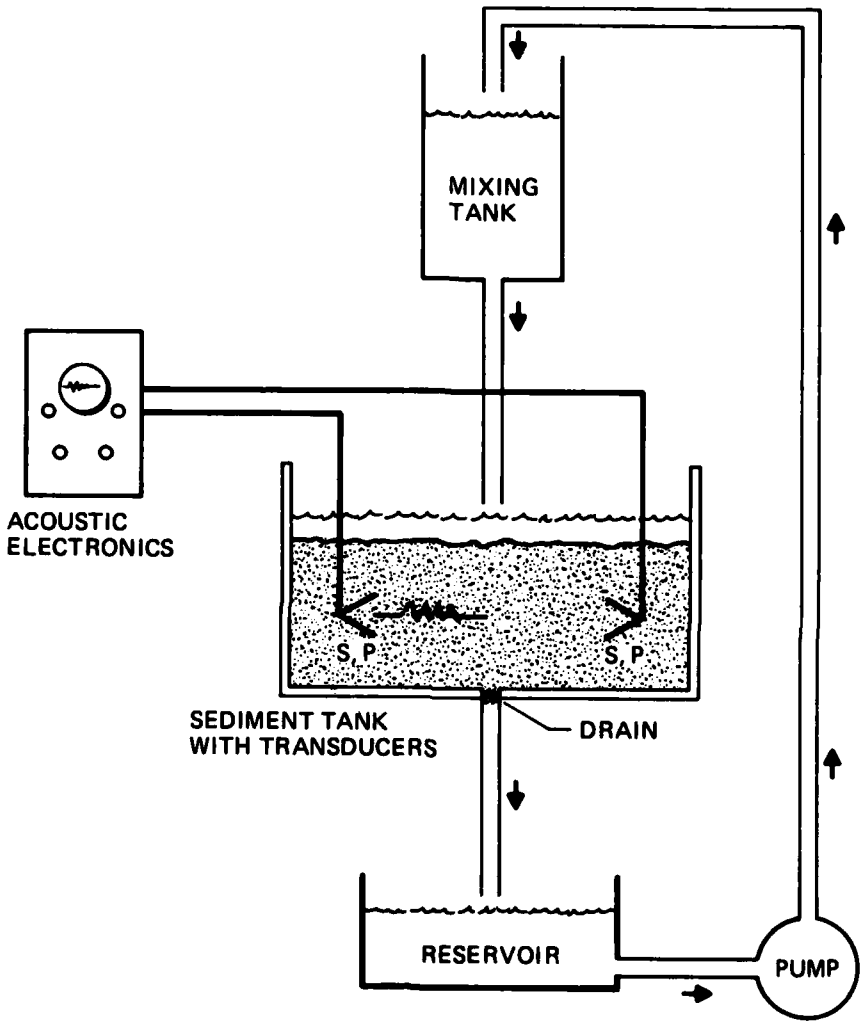

FIGURE 3
SCHEMATIC DIAGRAM OF EXPERIMENT

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C. Acoustical Measurements

The procedure for extracting acoustical data at any particular concentration of glycerol in the saturated fluid was to record data, then allow the apparatus to sit undisturbed for 24 hours, after which the measurements were repeated to ensure that a stable sediment had been obtained. Once a set of data was taken, a new concentration of glycerol was obtained by adding a quantity of pure glycerol (usually 400 ml) to the mixture tank. The fluid was then allowed to circulate in a closed fashion by flowing through the sediment tank to the reservoir, from which it was pumped up to the mixture tank, creating a continual flow. The viscosity and density of the fluid were tested periodically while circulation was in progress. When successive tests indicated that these properties were not changing as circulation continued, it was decided that a new stable solution had been reached. The last viscosity and density measurements recorded for this new solution were then used to determine the concentration of glycerol by weight in the solution. Afterwards, the apparatus remained undisturbed for at least 24 hours before acoustical data for the new solution were recorded. Then the cycle for a new solution began.

Successive measurements were made to a concentration of glycerol by weight of approximately 35%. Figures 4-7 give the measured acoustical data plotted as a function of glycerol concentration. Because the bead sizes differed from those of the work reported in Appendix A, the acoustical properties are different. This is clearly evident when shear wave velocities are compared.

Theoretical values of wave velocities and attenuations have been computed and are plotted as solid curves on Figs. 4-7. Although the diameter of the glass beads used in obtaining the present data was approximately four times the diameter of the beads that were used in our earlier work, several significant qualitative comparisons can be made.

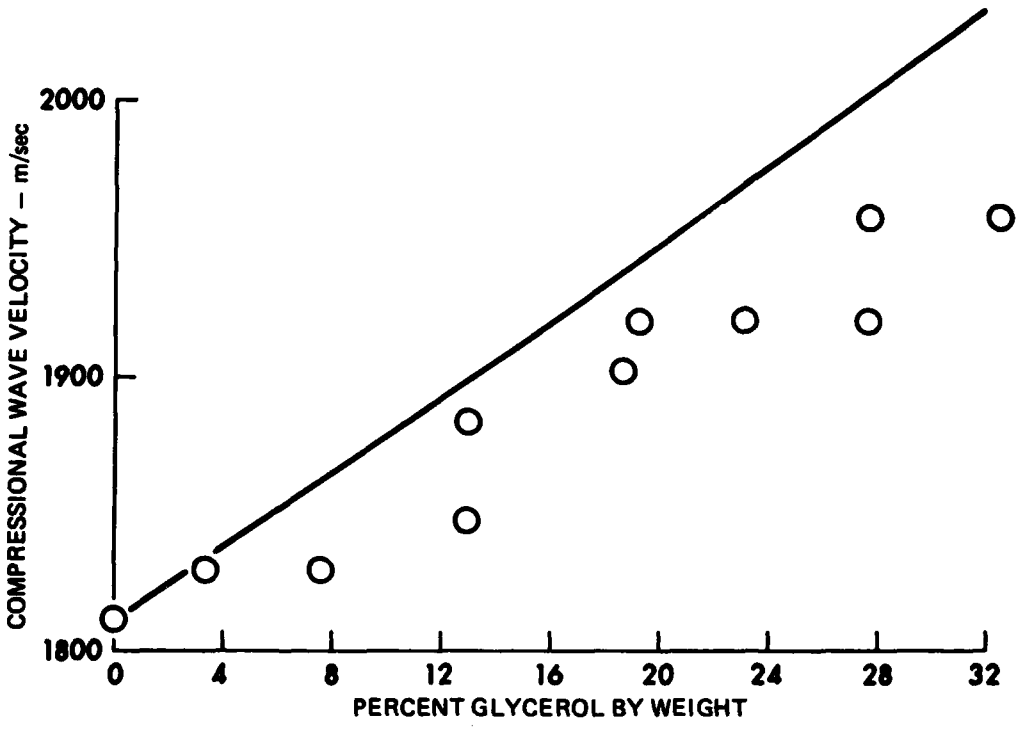

FIGURE 4
COMPRESSIONAL WAVE VELOCITY IN THE SATURATED SEDIMENT

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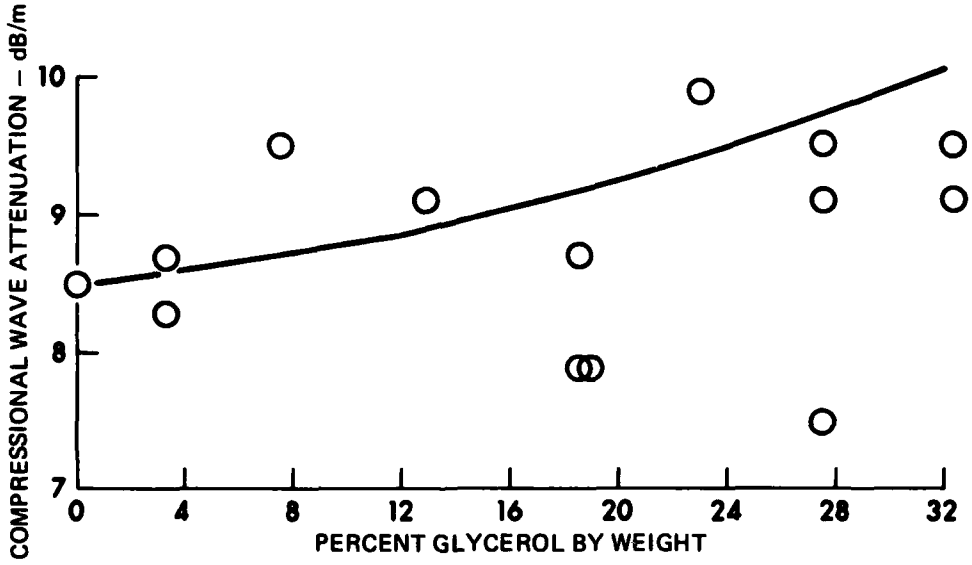

FIGURE 5
COMPRESSIONAL WAVE ATTENUATION IN THE SATURATED SEDIMENT

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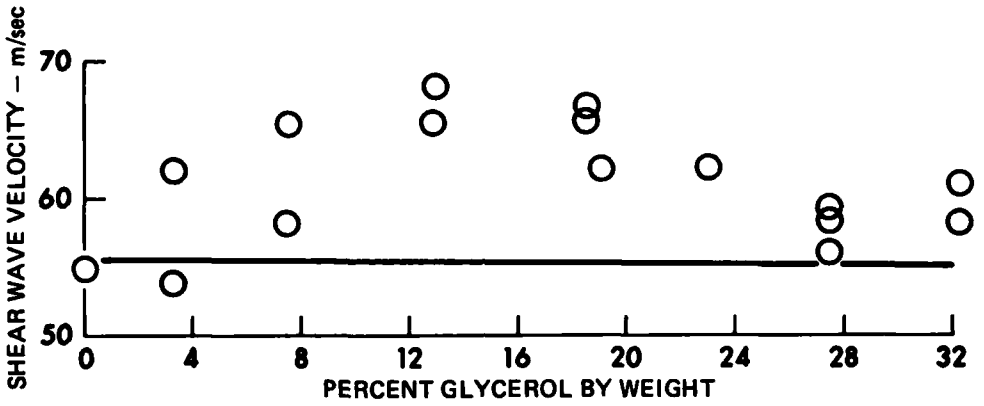

FIGURE 6
SHEAR WAVE VELOCITY IN THE SATURATED SEDIMENT

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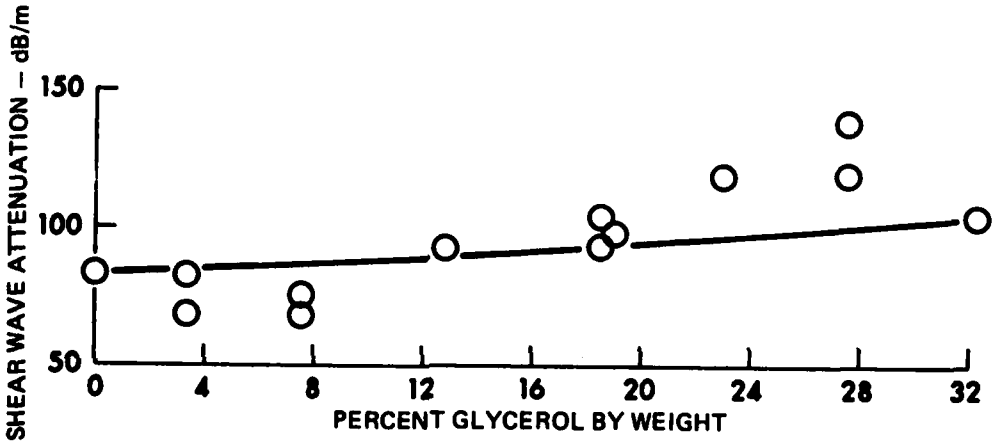

FIGURE 7
SHEAR WAVE ATTENUATION IN THE SATURATED SEDIMENT

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The agreement between the measured and theoretical compressional wave velocities (Fig. 4) is approximately the same as that of the earlier work. In the earlier work, the data on the compressional and shear wave attenuations showed larger increases with increasing glycerol concentration than were predicted by the theory. This is not observed in the new results (Figs. 5 and 7). Also, in the earlier work the data on the shear wave velocity were found to decrease more rapidly than was predicted by the theory. In the new results, the data actually increase, then decrease with increasing glycerol concentration---an observation which cannot be accounted for by the theory.

Thus, the new data are more consistent with the theoretical predictions of the attenuation, which may be attributable to the improved experimental procedure that was used. However, the new data also exhibit anomalous features (Fig. 6) which require further investigation.

REFERENCES

1. "The Bottom Interaction Program Five Year Plan for 1983," Ocean Programs Office, Naval Ocean Research and Development Agency, Code 530, NSTL Station, Mississippi.

2. M. Daniels and P. J. Vidmar, "The Occurrence and Acoustical Significance of Natural Gas Hydrates in Marine Sediments," to be published in J. Acoust. Soc. Am., October 1982.

3. S. K. Mitchell and K. C. Focke, "The Role of the Attenuation Profile in Low Frequency Shallow Water Propagation," submitted to J. Acoust. Soc. Am.

4. E. L. Hamilton, "Elastic Properties of Marine Sediments," J. Geophys. Res. 76, 579-604 (1971).

5. E. L. Hamilton, "Prediction of In Situ Acoustic and Elastic Properties of Marine Sediments," Geophys. 36, 266-284 (1971).

6. E. L. Hamilton, "Compressional Wave Attenuation in Marine Sediments," Geophys. 37, 620-646 (1972).

7. E. L. Hamilton, "Geoacoustic Models of the Sea Floor," in Physics of Sound in Marine Sediments, edited by L. D. Hampton (Plenum Press, New York, 1974), pp. 181-221.

8. E. L. Hamilton, "Geoacoustic Modeling of the Sea Floor," J. Acoust. Soc. Am. 68, 1313-1340 (1980).

9. W. M. Ewing, W. S. Jardetzky, and F. Press, Elastic Waves in Layered Media (McGraw-Hill Book Co., Inc., New York, 1957), pp. 272-278.

10. J. D. Ferry, Viscoelastic Properties of Polymers (John Wiley and Sons, Inc., New York, 1961).

11. J. E. White, Seismic Waves: Radiation, Transmission, and Attenuation (McGraw-Hill Book Co., Inc., New York, 1965).

12. M. A. Biot, "Theory of Elastic Waves in a Fluid Saturated Porous Solid. I. Low Frequency Range," J. Acoust. Soc. Am. 28, 168-178 (1956).

13. M. A. Biot, "Theory of Elastic Waves in a Fluid Saturated Porous Solid. II. Higher Frequency Range," J. Acoust. Soc. Am. 28, 179-191 (1956).

14. M. A. Biot, "Mechanics of Deformation and Acoustic Propagation in Porous Media," J. Appl. Phys. 33, 1482-1498 (1962).

15. M. A. Biot, "Generalized Theory of Acoustic Propagation in Porous Dissipative Media," J. Acoust. Soc. Am. 34, 1254-1264 (1962).

16. R. M. Bowen, "Theory of Mixtures in Continuum Physics," in Continuum Physics, Vol. III, Mixtures and EM Field Theories, edited by A. C. Eringen (Academic Press, New York, 1976).

17. A. Bedford and D. S. Drumheller, "A Variational Theory of Porous Media," Int. J. Solids Structures 15, 967-980 (1979).

18. M. A. Biot and D. G. Willis, "The Elastic Coefficients of the Theory of Consolidation," J. Appl. Mech. 24, 594-601 (1957).

19. R. D. Stoll and G. M. Bryan, "Wave Attenuation in Saturated Sediments," J. Acoust. Soc. Am. 47, 1440-1447 (1969).

20. R. D. Stoll, "Acoustic Waves in Saturated Sediments," in Physics of Sound in Marine Sediments, edited by L. D. Hampton (Plenum Press, New York, 1974).

21. R. D. Stoll, "Acoustic Waves in Ocean Sediments," Geophys. 42, 715-725 (1977).

22. R. D. Stoll, "Theoretical Aspects of Sound Transmission in Sediments," J. Acoust. Soc. Am. 68, 1341-1350 (1980).

23. J. M. Hovem and G. D. Ingram, "Viscous Attenuation of Sound in Saturated Sand," J. Acoust. Soc. Am. 66, 1807-1812 (1979).

24. R. D. Stoll, "Experimental Studies of Attenuation in Sediments," J. Acoust. Soc. Am. 66, 1152-1160 (1979).

25. D. J. Shirley, A. Bedford, and S. K. Mitchell, "Wave Propagation in a Saturated Model Sediment with Varied Liquid Properties" (in preparation).

26. R. D. Stoll and T. K. Kan, "Reflection of Acoustic Waves at a Water-Sediment Interface," J. Acoust. Soc. Am. 70, 149-156 (1981).

27. H. Deresiewicz and J. T. Rice, "The Effect of Boundaries on Wave Propagation in a Liquid Filled Porous Solid: III. Reflection of Plane Waves at a Free Plane Boundary (General Case)," Bull. Seismol. Soc. Am. 52, 595-625 (1962).

28. R. T. Bachman, "Acoustic Anisotropy in Marine Sediments and Sedimentary Rocks," J. Geophys. Res. 84, 7661-7663 (1979).

29. M. H. Manghnani, S. O. Schlanger, and P. D. Milholland, "Elastic Properties Related to Depth of Burial, Strontium Content and Age, and Diageneric Stage in Pelagic Carbonate Sediments," in Bottom Interacting Ocean Acoustics, edited by W. A. Kuperman and F. B. Jensen (Plenum Press, New York, 1980), pp. 41-51.

30. D. J. Shirley, "Acoustical Properties of Sediments," Applied Research Laboratories Technical Report No. 81-20 (ARL-TR-81-20), Applied Research Laboratories, The University of Texas at Austin, May 1981.

APPENDIX A

WAVE PROPAGATION IN A SATURATED MODEL SEDIMENT WITH VARIED LIQUID PROPERTIES

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Wave propagation in a saturated model sediment with varied liquid properties

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Experimental measurements have been made of the phase velocity and attenuation of compressional and shear waves in a bed of glass beads saturated by a mixture of water and glycerine. By varying the proportion of glycerine, a range of values of the viscosity, density and bulk modulus of the mixture was obtained. The data have been compared with theoretical predictions based upon the Biot theory.

INTRODUCTION

In order to predict the effects of the interaction of acoustic waves with the ocean bottom, it is necessary to have a comprehensive understanding of the propagation of waves in saturated sediments. Great progress toward such an understanding has recently been achieved by Stoll and Bryan[1], Stoll[2-4], and Hovem and Ingram[5]. These authors analyzed the propagation of waves in sediments by using the theory of fluid saturated porous media due to Biot[6-9].

Biot modeled the porous medium and the fluid as superimposed continua, and used a variational approach to derive equations of motion for the individual constituents. The equations contained drag terms associated with the relative velocity of the constituents, and also virtual mass terms associated with their relative acceleration. By using the solution for a cylinder containing viscous fluid and subjected to axial oscillations, Biot

was able to evaluate the coefficient of the drag term as a function of frequency. Furthermore, Biot and Willis[10] showed that the elastic coefficients in Biot's equations could be expressed in terms of the bulk moduli of the fluid and solid materials and the elastic moduli of the porous solid. In this regard also see the discussion by Stoll[11].

Stoll and Bryan were the first to apply Biot's equations to marine sediments. Unlike the porous elastic material which Biot had considered, the granular matrix materials in sediments were known to exhibit dissipative effects. They therefore assumed that the moduli of the solid material were complex. On the basis of experimental data on dry granular materials, they assumed that these complex moduli were not frequency dependent[12]. Using this approach, Stoll subsequently showed that the theory could correctly predict the variation with frequency of the attenuation of compressional waves in saturated sands[13]. He also pointed out that dissipation due to relative motion of the fluid and solid was the dominant loss mechanism at higher frequencies, while losses associated with the granular matrix were dominant at low frequency.

Hovem and Ingram were able to show that the technique used by Biot to evaluate the drag term in the equations could also be used to evaluate the coefficient of the virtual mass term as a function of frequency[14]. They showed that the theory compared favorably with measurements of compressional wave attenuation in saturated sands. In addition, they presented new experimental data on compressional waves in a model sediment consisting of spherical glass beads saturated by water, and showed that the theory correctly predicted both the attenuation and phase velocity as functions of frequency.

In this paper, results are presented of measurements of phase velocity and attenuation of compressional and shear waves in a glass bead model sediment of the type used by Hovem and Ingram. The novel aspect of the measurements was that a mixture of water and glycerine was used as the saturating fluid. By changing the proportion of glycerine in the fluid, data was obtained for a range of values of the viscosity, density and bulk modulus of the fluid. Since these parameters appear explicitly in the extended Biot equations developed by Stoll-Bryan and Hovem-Ingram, the measurements provide a critical test of the theory.

I. EXPERIMENTAL MEASUREMENTS

When glycerine is added to water, the density, viscosity and bulk modulus of the mixture are larger than the values for water. Published data are available for the density and viscosity of a water-glycerine solution at 20°C as a function of the percent of glycerine by weight[15]. For $0 \leq W \leq 28$, where W is the percent of glycerine by weight, the data on the density ρ_f (g/cm^3) and viscosity η (Poise) of the mixture can be approximated by the empirical equations

$$\rho_f = 0.9982 + (2.284 \times 10^{-3})\, W + (4.067 \times 10^{-6})\, W^2 + (4.960 \times 10^{-8})\, W^3 , \quad (1)$$

$$\eta = 0.01002 + (2.461 \times 10^{-4})\, W + (2.500 \times 10^{-6})\, W^2 + (1.786 \times 10^{-7})\, W^3 . \quad (2)$$

As part of this study, measurements were made of the wave velocity and attenuation in the water-glycerine mixture. The measurements were made at a frequency of 114 kHz (the higher of the two frequencies used in the model sediment measurements). The wave velocity data are shown in Fig. 1. No variation in the wave attenuation due to the addition of glycerine was observed. Once the wave velocity was known, it was used together with the data on the density to compute the bulk modulus of the mixture as a function of the percent of glycerine by weight (Fig. 2). For $0 \leq W \leq 28$, the bulk modulus of the mixture, K_f (dyne/cm^2), can be approximated by

$$K_f = [2.175 + (2.052 \times 10^{-2})\, W + (1.400 \times 10^{-4})\, W^2 - (1.667 \times 10^{-7})\, W^3] \times 10^{10} . \qquad (3)$$

The solid matrix material consisted of a bed of nominally spherical glass beads of 0.0177 cm diameter. The density of the glass was 2.5 g/cm^3 and the porosity of the bed was 0.365.

The measurements of wave velocity and attenuation were made in a sediment tank 16 cm x 30 cm x 20 cm deep. The depth of the transducers in the sediment was approximately 10 cm.

The sediment sample was prepared by adding demineralized water to the initially dry material, boiling the mixture and then subjecting the cooled sediment to a vacuum for 24 hours. Once the sediment was ready for measurement, the transducers were inserted into the material and the apparatus allowed to remain undisturbed for another 24 hours. Acoustical measurements were then

made and the sediment was allowed to sit undisturbed for another 24 hours, after which the acoustical measurements were repeated. This procedure was repeated until successive shear wave measurements were essentially identical. It was usually found that the sediment was stabilized by the third or fourth 24 hour interval.

Once a set of measurements had been made, the sediment was removed from the tank, approximately 400 ml of glycerin added and the new mixture thoroughly stirred. The sediment was again evacuated to remove entrained air and the measurement procedure described above was repeated. After the acoustical measurements were completed for a particular concentration of glycerin, a sample of the pore fluid was removed from the tank for viscosity and density measurements. Viscosity was measured at 20°C with a modified Ostwalt viscometer and density was measured at 20°C with a calibrated 50 ml picnometer. The viscosity and density measurements were used to determine concentration.

After successive measurements to a concentration of approximately 25% glycerin, the sediment was discarded and the whole procedure repeated with freshly prepared sediment as a check.

The transducers that were used to make the compressional and shear wave measurements were similar to those described by Shirley[16], and consisted of a shear wave bender element mounted so that the plane of the bender was vertical, and a small compressional wave element near the bender element. One projector was used with two receivers so that attenuation could be calculated from the difference in amplitude of signals from the receivers. Compressional wave data were measured at a frequency of 114 kHz and shear wave data were measured at 2.8 kHz.

In Fig. 3, the measured compressional phase velocity is plotted as a function of glycerine concentration. (The curves on Figs. 3-6 will be discussed in Part II of the paper.) The phase velocity increases approximately linearly with increasing concentration and there is little scatter in the data. The increase in the velocity occurs primarily due to the increasing bulk modulus of the fluid (Fig. 2).

Note that the measured value of the phase velocity with no glycerine present differs from the compressional phase velocity measured at the same frequency by Hovem and Ingram[17] by over 100 m/s. The difference is due to Hovem and Ingram's measurements being made at a depth of 20 cm in the sediment, compared to a depth of 10 cm for the present measurements. This is an example of the strong depth dependence of the acoustic properties of saturated sediments[18,19].

The measured compressional wave attenuation is plotted in Fig. 4. The data exhibits substantial scatter, but suggests an approximately linear increase in attenuation with increasing concentration. Increased attenuation would be expected since the drag arising from the relative motion of the fluid and solid increases with increasing viscosity of the fluid. However, it will be shown in Part II that this mechanism alone does not explain the observed increase.

The measured shear phase velocity is plotted in Fig. 5. Again there is substantial scatter, but the data suggests a decrease in the velocity with increasing concentration.

The measured shear wave attenuation is plotted in Fig. 6. As with the compressional attenuation, the data indicate a substantial increase in attenuation with increasing glycerine concentration.

II. THEORETICAL COMPARISONS

Biot's equations[20] can be written, in Cartesian tensor notation,

$$(1 - \phi)\,\rho_s \frac{\partial^2}{\partial t^2} u_{(s)m} = - c \frac{\partial^2}{\partial t^2} (u_{(s)m} - u_{(f)m}) + A e_{(s)kk,m} + 2\mu_b e_{(s)mk,k} + Q\, e_{(f)kk,m} - b \frac{\partial}{\partial t} (u_{(s)m} - u_{(f)m}) , \tag{4}$$

$$\phi\,\rho_f \frac{\partial^2}{\partial t^2} u_{(f)m} = c \frac{\partial^2}{\partial t^2} (u_{(s)m} - u_{(f)m}) + Q\, e_{(s)kk,m} + R\, e_{(f)kk,m} + b \frac{\partial}{\partial t} (u_{(s)m} - u_{(f)m}) , \tag{5}$$

where ϕ is the porosity, ρ_s and ρ_f are the mass densities of the solid and fluid, $u_{(s)m}$ and $u_{(f)m}$ are the displacement vectors of the solid and fluid, the notation $,m$ denotes partial differentiation with respect to the coordinate x_m, $e_{(s)mk}$ and $e_{(f)mk}$ are the linear strains of the solid and fluid $(e_{(s)mk} = \frac{1}{2}(u_{(s)m,k} + u_{(s)k,m}))$, and A, $\bar{\mu}_b$, Q, R, c and b are constitutive coefficients. The first terms on the right of Eqs. (4) and (5) are the virtual mass terms and the last terms on the right are the drag terms.

By introducing the notation

$$e = u_{(s)m,m} \ , \ \zeta = \phi \ (u_{(s)m,m} - u_{(f)m,m}) \tag{6}$$

and taking the divergence of Eqs. (4) and (5), they can be written

$$\frac{\partial^2}{\partial t^2} (\rho e - \rho_f \zeta) = He_{,mm} - C\zeta_{,mm} \ , \tag{7}$$

$$\frac{\partial^2}{\partial t^2} (\rho_f e - \rho_c \zeta) = Ce_{,mm} - M\zeta_{,mm}$$

$$+ \frac{b}{\phi^2} \frac{\partial}{\partial t} \zeta \ , \tag{8}$$

where $\rho = (1 - \phi) \rho_s + \phi \rho_f$ is the mass density of the fluid-solid mixture and

$$\begin{aligned} H &= A + 2\bar{\mu}_b + 2Q + R \ , \\ C &= (Q + R) / \phi \ , \\ M &= R / \phi^2 \ , \\ \rho_c &= \rho_f / \phi + c / \phi^2 \ . \end{aligned} \tag{9}$$

Equations (7) and (8) are essentially the forms of Biot's equations for compressional waves used by Stoll and Hovem and Ingram. Hovem and Ingram extended Biot's analysis[21] and evaluated the coefficients b and c as functions of frequency. Their results were

$$b / \phi^2 = \eta \text{ Real } (F(\kappa)) / B_o ,$$

$$c / \phi^2 = \eta \text{ Imaginary } (F(\kappa)) / (\omega B_o) , \tag{10}$$

where η is the viscosity of the liquid, ω is the frequency (rad/s), and

$$\kappa = a_p \, (\omega \rho_f / \eta)^{\frac{1}{2}} . \tag{11}$$

The term a_p is a pore size parameter defined by

$$a_p = \phi \, d_m / [3(1 - \phi)] \tag{12}$$

and d_m is the diameter of the spherical grains of the sediment. The function $F(\kappa)$ is[22]

$$F(\kappa) = \frac{1}{4} \kappa T(\kappa) / [1 - 2T(\kappa) / i\kappa] , \tag{13}$$

where $T(\kappa)$ is the Kelvin function

$$T(\kappa) = [\text{ber}'(\kappa) + i \, \text{bei}'(\kappa)] / [\text{ber}(\kappa) + i \, \text{bei}(\kappa)] . \tag{14}$$

permeability B_o is

$$B_o = \phi\, a_p^2 / 4\, k\,, \tag{15}$$

where k is the Kozeny-Carman constant. For the glass beads used in the present study, Bell[23] obtained a value $k = 3.98$ on the basis of direct measurements of the permeability.

The expressions for the coefficients H, C and M in terms of the bulk moduli of the solid and fluid materials K_s, K_f and the bulk and shear moduli of the drained granular matrix material $\bar{K}_b$, $\bar{\mu}_b$ are[24]

$$H = (K_s - \bar{K}_b)^2 / (D - \bar{K}_b) + \bar{K}_b + 4\bar{\mu}_b / 3\,,$$

$$C = K_s\,(K_s - \bar{K}_b) / (D - \bar{K}_b)\,, \tag{16}$$

$$M = K_s^2 / (D - \bar{K}_b)\,,$$

where

$$D = K_s\,[1 + \phi\,(K_s / K_f - 1)]\,. \tag{17}$$

By introducing the notation

$$\underset{\sim}{\omega} = \text{curl}\ \underset{\sim}{u}_{(s)}\,,\ \underset{\sim}{\theta} = \phi\ \text{curl}\ (\underset{\sim}{u}_{(s)} - \underset{\sim}{u}_{(f)}) \tag{18}$$

and taking tne curl of Eqs. (4) and (5), the Biot equations for shear waves can be written

$$\frac{\partial^2}{\partial t^2}(\rho\omega_m - \rho_f\,\theta_m) = \bar{\mu}_b\,\omega_{m,kk}\ , \tag{19}$$

$$\frac{\partial^2}{\partial t^2}(\rho_f\,\omega_m - \rho_c\,\theta_m) = \frac{b}{\phi^2}\frac{\partial}{\partial t}\theta_m\ . \tag{20}$$

In order to introduce damping due to friction at the grain to grain contacts, Stoll and Bryan assumed that the moduli of the drained granular matrix, $\bar{K}_b$ and $\bar{\mu}_b$, were complex constants,

$$\bar{K}_b = K_b + i\,K_b'\ , \tag{21}$$

$$\bar{\mu}_b = \mu_b + i\,\mu_b'\ . \tag{21}$$

In terms of logarithmic decrements δ_c and δ_s, the imaginary parts of the moduli are[25]

$$K_b' = \delta_c\,K_b\,/\,\pi\ ,$$

$$\mu_b' = \delta_s\,\mu_b\,/\,\pi\ . \tag{21}$$

Equations (1) - (21) have been used to determine compressional and shear phase velocities and attenuations for comparison with the measurements

described in Part I. With the exception of the moduli $\bar{K}_b$ and $\bar{\mu}_b$, the parameters in the equations are known in terms of the physical properties of the fluid and solid constituents, and are summarized in Table I.

In determining $\bar{K}_b$ and $\bar{\mu}_b$ it was assumed, following Hovem and Ingram[26], that $K_b = \mu_b$, which corresponds to a Poisson's ratio of the solid matrix material of 0.125. This is within the range of 0.1 to 0.17 which Stoll[27] suggests for a granular material. The values of μ_b and δ_s were then chosen so that the theoretical values of the shear phase velocity and attenuation agreed with the data for zero percent glycerine. (Note from Eqs. (19) and (20) that the shear phase velocity and attenuation are independent of $\bar{K}_b$.) It was found that values of $\mu_b = 8 \times 10^7$ dyne/cm^2 and $\delta_s = 0$ gave a shear phase velocity of 66.94 m/s and a shear attenuation of 68.41 dB/m. Increasing δ_s to 0.1 gave a shear phase velocity of 67.00 m/s and a shear attenuation of 104.70 dB/m, which agree with the averages of the measured values. Next, using the latter values for μ_b and δ_s and assuming that $K_b = \mu_b$ and $\delta_c = 0$ gave a compressional phase velocity of 1807.89 m/s and a compressional attenuation of 30.91 dB/m. These values agree quite well with the measurements. Increasing δ_c to 0.1 had a very small effect on the compressional attenuation, increasing it to 30.93 dB/m.

Then, using the values $K_b = \mu_b = 8 \times 10^7$ dyne/cm^2 and $\delta_s = \delta_c = 0.1$, the compressional and shear phase velocity and attenuation were determined as functions of glycerine concentration. The results are indicated by the solid curves in Figs. 3-6.

The increase in the compressional phase velocity with increasing glycerine concentration, due primarily to the increasing bulk modulus of the

fluid, is predicted very well by the theory (Fig. 3). The theory predicts a slight decrease in the shear phase velocity with increasing concentration due to the increasing density of the fluid. The data suggest a larger decrease, but this remains conjectural due to the scatter of the data.

For both compressional and shear attenuation, the data indicate a substantially larger increase with increasing concentration than is predicted by the theory. The slight increase in attenuation predicted by the theory is due to the dependence of the drag on the viscosity of the fluid. This mechanism clearly does not account for the measured attenuation. Thus the data indicate that there is viscous dissipation present which is a function of the viscosity of the liquid.

The possibility of viscous dissipation of this type has been discussed by Stoll[28]. He stated that "... in a general model, it may be necessary to allow for both frictional and viscous losses in the parameters that describe the response of the skeletal frame, particularly if high frequencies are to be considered."

For the shear waves, a determination was made of the value of the shear logarithmic decrement necessary for the theory to predict the measured attenuation. This was done for each data point in Fig. 6. The resulting values are plotted in Fig. 7 as a function of the viscosity of the fluid. The logarithmic decrement increases approximately linearly with increasing viscosity of the fluid. It is interesting to note from Fig. 7 that the data appear to be approaching the horizontal axis at a finite value of the viscosity ($\simeq$ 0.007 Poise). There may be a threshold value of the viscosity below which the fluid does not affect the viscoelastic response of the matrix material.

The values of the shear logarithmic decrement plotted in Fig. 7 were approximated by the linear relation (shown on the figure)

$$\delta_s = -0.241 + 35.7\eta \ . \tag{22}$$

Equation (22) was then used in the theory to determine the shear wave attenuation as a function of glycerince concentration. The result is shown as the dashed curve in Fig. 6.

The situation with regard to interpretation of the compressional wave data was more complex. While the shear wave attenuation does not depend upon $\bar{K}_b$, the compressional wave attenuation depends upon both $\bar{K}_b$ and $\bar{\mu}_b$. Furthermore, the compressional and shear measurements were made at different frequencies. Since viscous dissipation would depend upon frequency, the shear measurements could not be used to evaluate $\bar{\mu}_b$ at the frequency at which the compressional measurements were made.

In order to obtain an estimate, it was assumed that the compressional and shear logarithmic decrements were equal, $\delta_c = \delta_s$. It was found that for 26 percent glycerine, a value $\delta_c = 35$ resulted in a compressional phase velocity of 1983.67 m/s and a compressional attenuation of 53.11 dB/m, in agreement with the data. Note that this logarithmic decrement is approximately seventy times the value of δ_s required to match the shear wave attenuation. The ratio of the frequency for the compressional measurements to the frequency for the shear measurements was approximately forty. This strongly suggests that the loss parameters are frequency dependent.

It is obvious that the value 35 is completely unrealistic if δ_c is interpreted literally as a logarithmic decrement. The reason for the large value can be seen by an examination of Eqs. (7), (16) and (17). Note from Eq. (7) that H is the compressional modulus of the fluid-solid mixture when the strains in the fluid and solid are equal. Since $K_b << K_s$ in the case being considered, it can be seen from Eqs. (16) and (17) that a relatively large change in $\bar{K}_b$ is necessary to cause a substantial change in H. The magnitude of K_b' should perhaps be compared to the real part of H, rather than with K_b. In the present case, K_b' / Real (H) = 0.0132.

ACKNOWLEDGMENT

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Figure Captions

Fig. 1 Compressional wave velocity in the water-glycerine mixture.

Fig. 2 Bulk modulus of the water-glycerine mixture.

Fig. 3 Compressional phase velocity in the saturated sediment.

Fig. 4 Compressional wave attenuation in the saturated sediment.

Fig. 5 Shear phase velocity in the saturated sediment.

Fig. 6 Shear wave attenuation in the saturated sediment.

Fig. 7 Computed shear logarithmic decrement as a function of fluid viscosity.

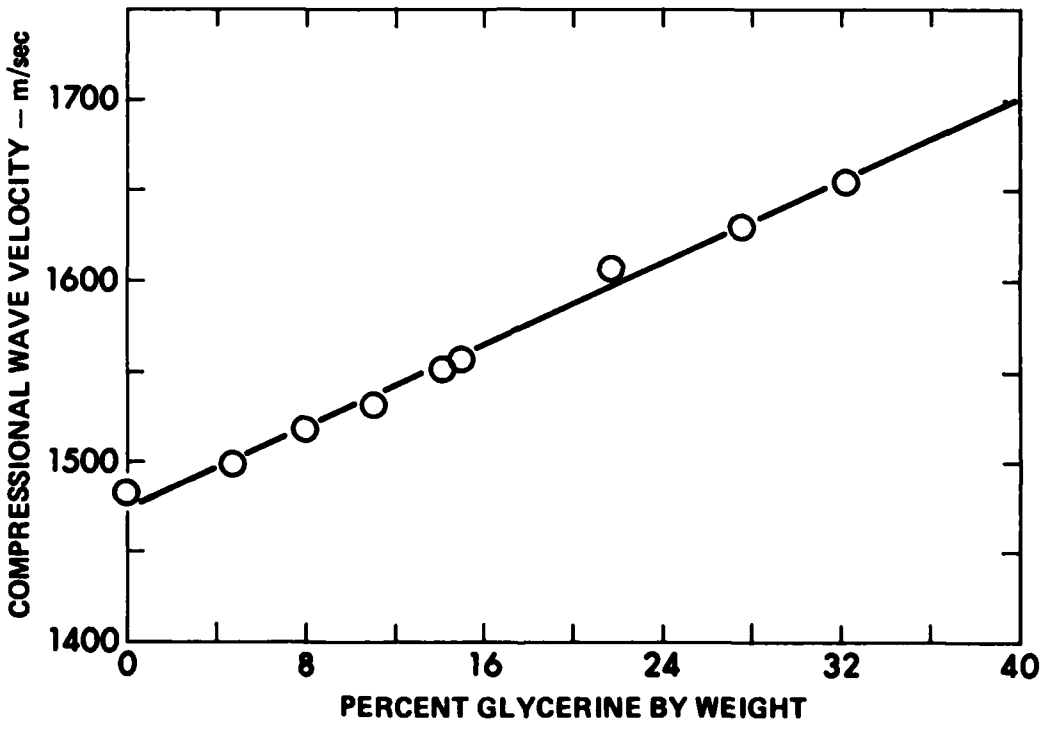

Fig. 1
Bedford

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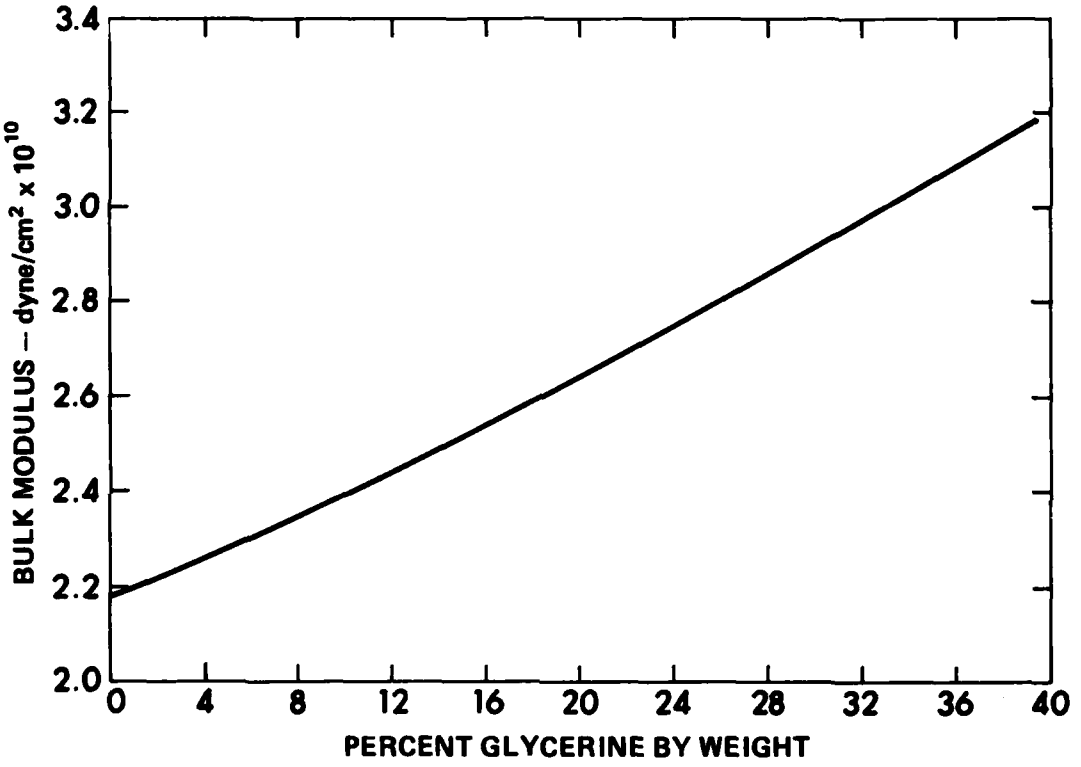

Fig. 2
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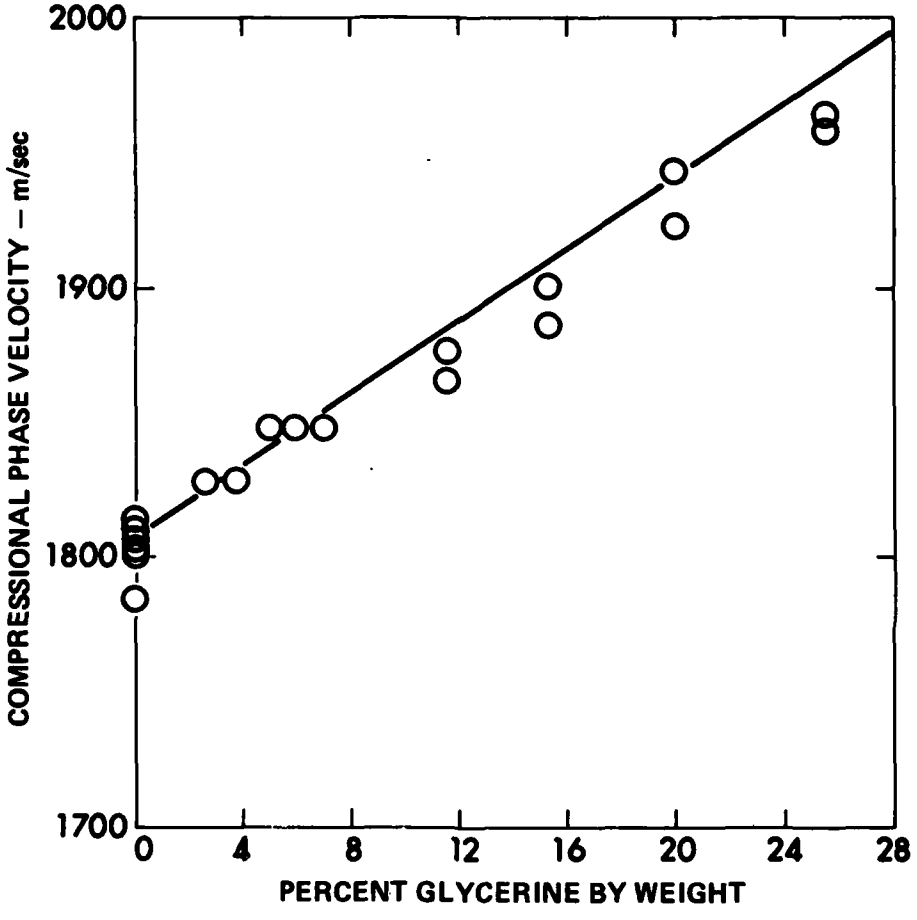

Fig. 3
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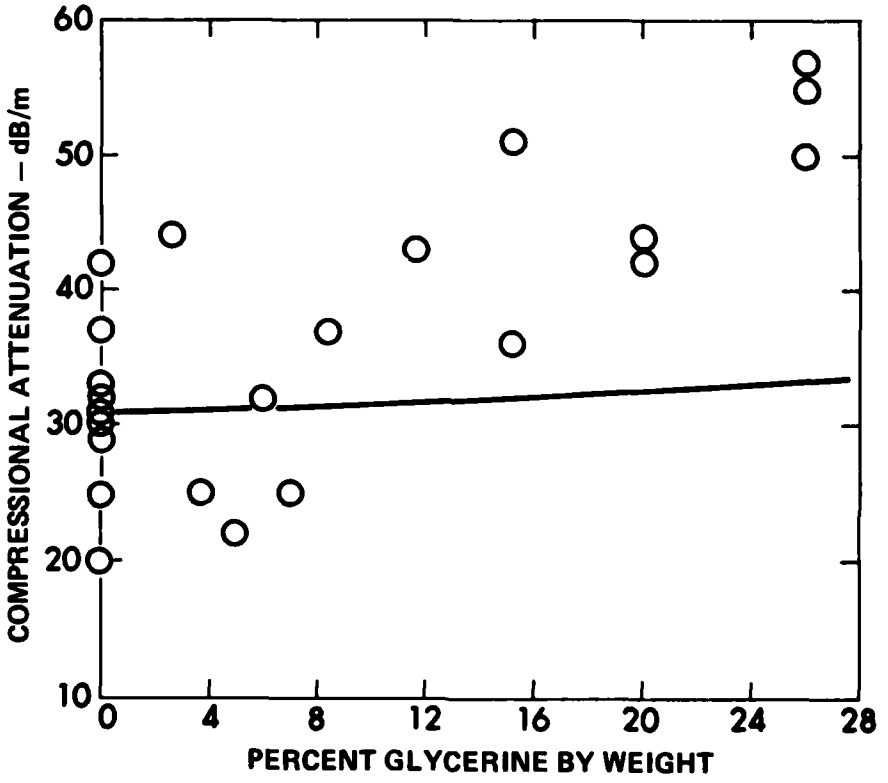

Fig. 4
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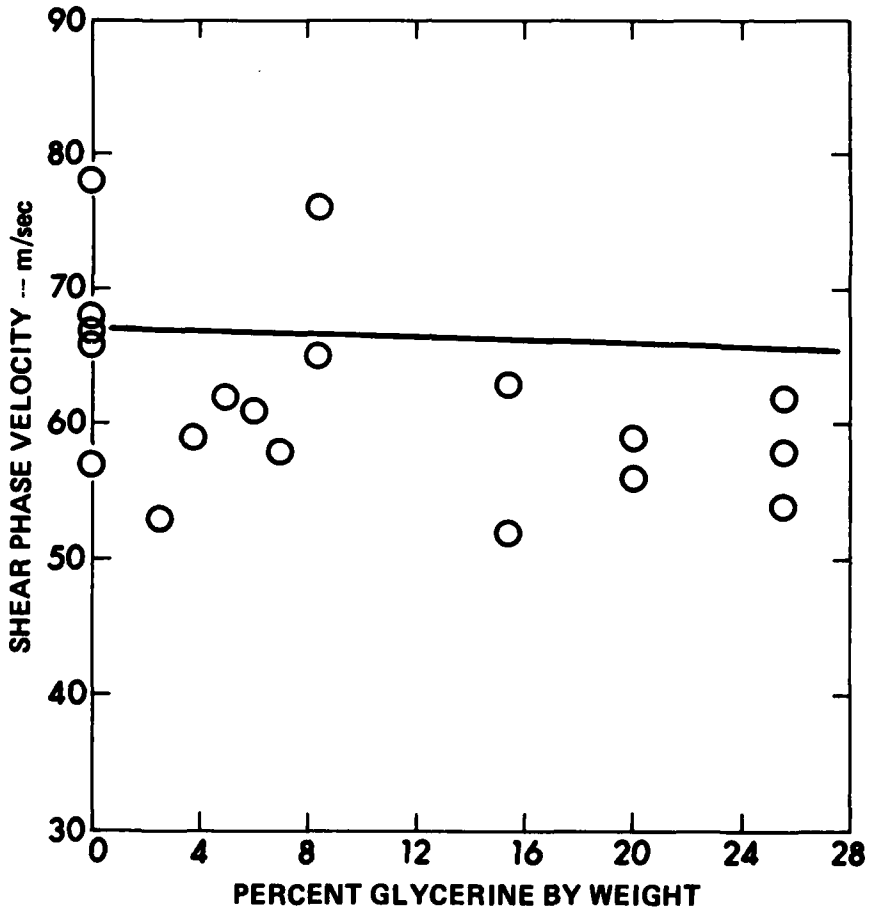

Fig. 5
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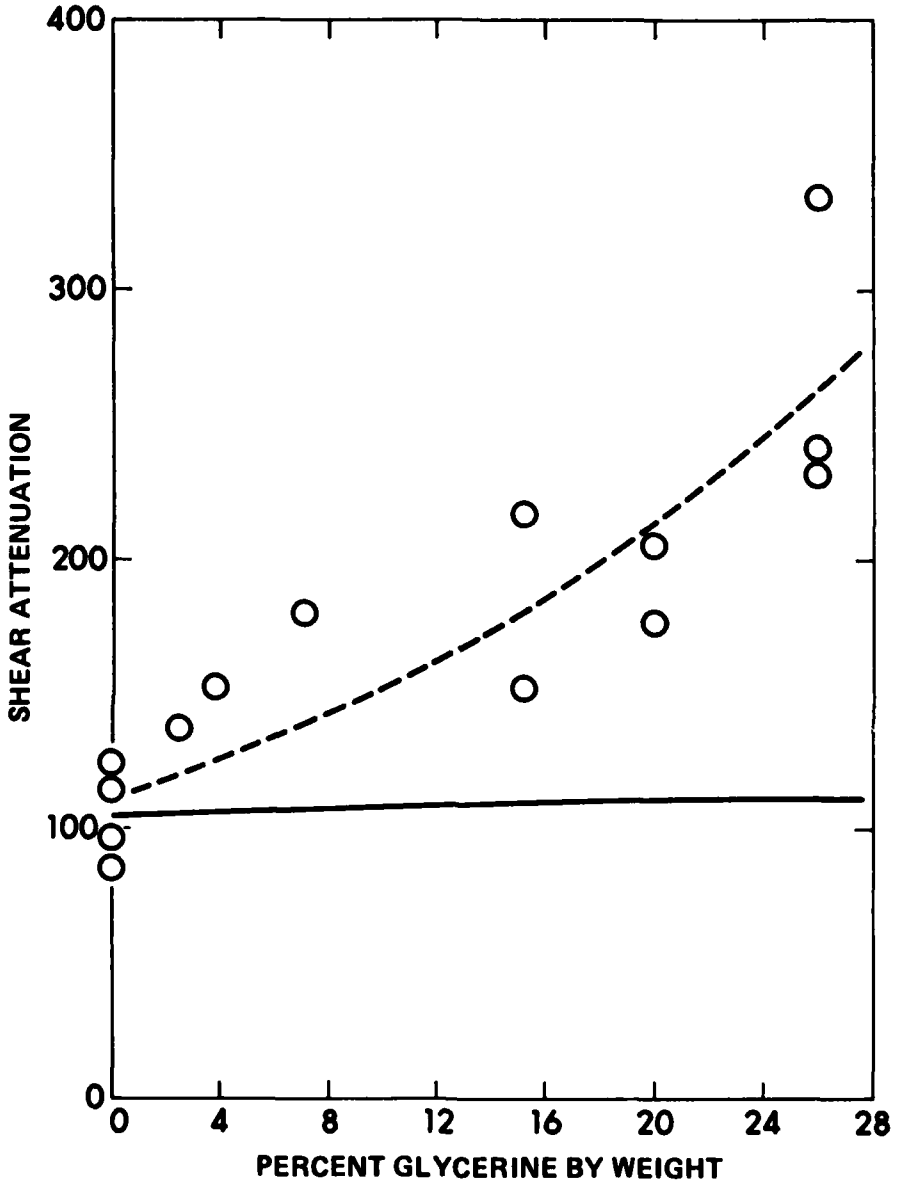

Fig. 6
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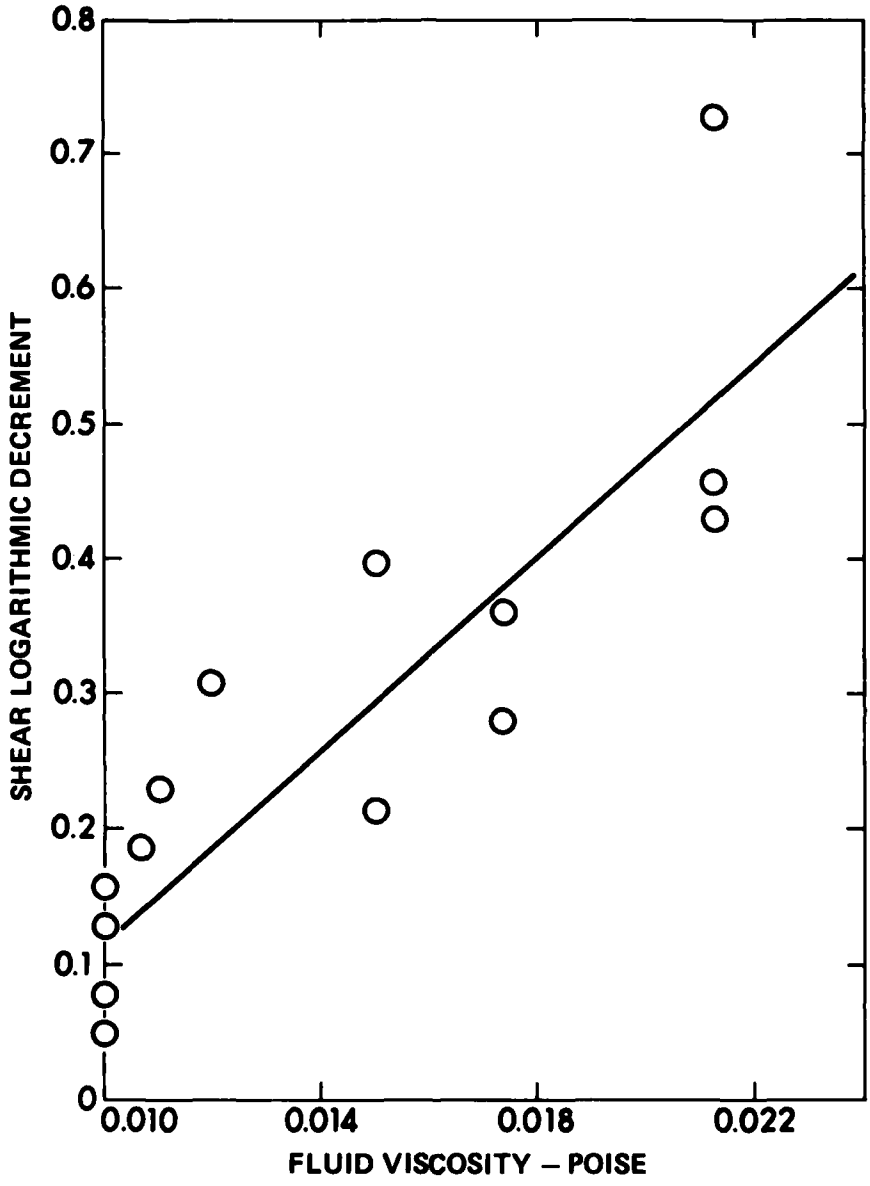

Fig. 7
Bedford

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Table I. Material Constants and Parameters

Porosity, ϕ	0.365
Bead diameter, d_m	0.0177 cm
Solid material density, ρ_s	2.5 g/cm^3
Fluid density, ρ_f	From Eq. (1)
Fluid viscosity, η	From Eq. (2)
Solid material bulk modulus, K_s	3.5 x 10" dyne/cm^2
Fluid bulk modulus, K_f	From Eq. (3)
Kozeny-Carman constant, k	3.98

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[1]R. D. Stoll and G. M. Bryan, "Wave attenuation in saturated sediments," J. Acoust. Soc. Am. 47, 1440-1447 (1969).

[2]R. D. Stoll, "Acoustic waves in saturated sediments," in Physics of Sound in Marine Sediments, edited by L. D. Hampton (Plenum, New York, 1974).

[3]R. D. Stoll, "Acoustic waves in ocean sediments," Geophys. 42, 715-725 (1977).

[4]R. D. Stoll, "Theoretical aspects of sound transmission in sediments," J. Acoust. Soc. Am. 68, 1341-1350 (1980).

[5]J. M. Hovem and G. D. Ingram, "Viscous attenuation of sound in saturated sand," J. Acoust. Soc. Am. 66, 1807-1812 (1979).

[6]M. A. Biot, "Theory of elastic waves in a fluid saturated porous solid. I. Low frequency range," J. Acoust. Soc. Am. 28, 168-178 (1956).

[7]M. S. Biot, "Theory of elastic waves in a fluid saturated porous solid. II. Higher frequency range," J. Acoust. Soc. Am. 28, 179-191 (1956).

[8]M. A. Biot, "Mechanics of deformation and acoustic propagation in porous media," J. Appl. Phys. 33, 1482-1498 (1962).

[9]M. A. Biot, "Generalized theory of acoustic propagation in porous dissipative media," J. Acoust. Soc. Am. 34, 1254-1264 (1962).

[10]M. A. Biot and D. G. Willis, "The elastic coefficients of the theory of consolidation," J. Appl. Mech. 24, 594-601 (1957).

[11]Ref. 2, pp. 21-25.

[12]Ref. 1, 1442.

[13]Ref. 2, Fig. 4.

[14]Ref. 5, pp. 1807-1809.

[15]CRC Handbook of Chemistry and Physics, edited by R. C. Weast (CRC Press, West Palm Beach, Florida, 1978), pp. D-277, 278.

[16]D. J. Shirley, "An improved shear wave transducer," J. Acoust. Soc. Am. 63, 1643-1645 (1978).

[17]Ref. 5, Fig. 3.

[18]Ref. 4, pp. 1343, 1346.

[19]E. L. Hamilton, "Geoacoustic modeling of the sea floor," J. Acoust. Soc. Am. 68, 1313-1340 (1980).

[20]Ref. 6, Eq. (6.7).

[21]Ref. 7, pp. 180-185.

[22]It should be noted that Ref. 5 contains misprints in the equations for $F(\kappa)$ and $T(\kappa)$.

[23]D. W. Bell, "Shear wave propagation in unconsolidated fluid saturated porous media," Report ARL-TR-79-31, Applied Research Laboratories, University of Texas at Austin (1979).

[24]Ref. 2, Eq. (13).

[25]Ref. 2, p. 32.

[26]Ref. 5, p. 1810.

[27]Ref. 4, p. 1345

[28]Ref. 4, pp. 1343-1345

APPENDIX B

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S. R. Addy, E. W. Behrens, T. R. Haines, D. J. Shirley, and J. L. Worzel, "Correlation of Some Lithologic and Physical Characteristics of Sediments with High Frequency Subbottom Reflection Types," Proceedings of the 11th Annual Offshore Technology Conference, Houston, Texas, 30 April - 3 May 1979.

A. L. Anderson, "Acoustics of Gas-Bearing Sediments," Applied Research Laboratories Technical Report No. 74-19 (ARL-TR-74-19), Applied Research Laboratories, The University of Texas at Austin, May 1974.

A. L. Anderson and L. D. Hampton, "In Situ Measurement of Sediment Acoustic Properties During Coring," presented at the ONR Symposium on Physical and Engineering Properties of Deep-Sea Sediments, Airlie House, Airlie, Virginia, 24-27 April 1973.

A. L. Anderson and L. D. Hampton, "Measurement of In Situ Acoustic Properties During Sediment Coring," presented at the ONR Symposium on the Physics of Sound in Marine Sediments, Lakeway Inn, Austin, Texas, 8-10 May 1973.

A. L. Anderson and L. D. Hampton, "A Method for Measuring In Situ Acoustic Properties During Sediment Coring," In Physics of Sound in Marine Sediments, edited by Loyd Hampton (Plenum Press, 1974).

A. L. Anderson and L. D. Hampton, "In Situ Measurements of Sediment Acoustic Properties During Coring," In Deep-Sea Sediments, Physical and Mechanical Properties, edited by A. L. Inderbitzen (Plenum Press, 1974).

A. L. Anderson and L. D. Hampton, "Use of Tubes for Measurement of Acoustical Properties of Materials," presented at the 89th Meeting of the Acoustical Society of America, Austin, Texas, April 1975.

A. L. Anderson and L. D. Hampton, "Acoustics of Gas-Bearing Sediments. Part I: Background," Applied Research Laboratories Technical Paper No. 79-63 (ARL-TP-79-63), Applied Research Laboratories, The University of Texas at Austin, October 1979.

A. L. Anderson and L. D. Hampton, "Acoustics of Gas-Bearing Sediments. Part II: Measurements and Models," Applied Research Laboratories Technical Paper No. 79-64 (ARL-TP-79-64), Applied Research Laboratories, The University of Texas at Austin, October 1979.

A. L. Anderson and L. D. Hampton, "Acoustics of Gas-Bearing Sediments. Part I: Background," J. Acoust. Soc. Am. 67, 1865-1889 (1980).

A. L. Anderson and L. D. Hampton, "Acoustics of Gas-Bearing Sediments. Part II: Measurements and Models," J. Acoust. Soc. Am. 67, 1890-1903 (1980).

A. L. Anderson, R. J. Harwood, and L. D. Hampton, "Temperature Studies on Lake Travis Stratification in a Warm Monomictic Reservoir," The Texas Journal of Science, Vol. XXVI, Nos. 3 and 4, 353-371, August 1975.

D. W. Bell, "Shear Wave Propagation in Unconsolidated Fluid Saturated Porous Media," Dissertation for Ph.D. awarded by The University of Texas at Austin, May 1979. Also Applied Research Laboratories Technical Report No. 79-31 (ARL-TR-79-31), Applied Research Laboratories, The University of Texas at Austin, May 1979.

D. W. Bell and D. J. Shirley, "Temperature Variation of the Acoustical Properties of Laboratory Sediments," Applied Research Laboratories Technical Paper No. 80-1 (ARL-TP-80-1), Applied Research Laboratories, The University of Texas at Austin, January 1980.

D. W. Bell and D. J. Shirley, "Temperature Variation of the Acoustical Properties of Laboratory Sediments," J. Acoust. Soc. Am. 68, 227-231 (1980).

L. D. Hampton, "ARL Experience with Acoustics and Gas in Sediments," presented at Symposium on Natural Gases in Marine Sediments and Their Mode of Distribution, The University of California Lake Arrowhead Conference Center, Lake Arrowhead, California, 28-30 November 1972.

L. D. Hampton and A. L. Anderson, "Acoustics and Gas in Sediments": Applied Research Laboratories (ARL) Experience," in Natural Gases in Marine Sediments, Marine Science Vol. III, Edited by Isaac R. Kaplan (Plenum Press, 1974).

J. M. Hovem, "Some Aspects of Sound Propagation in Saturated Sand," presented at the Seminar on Bottom Effects in Underwater Sound Propagation, Miami, Florida, 26-28 April 1979.

J. M. Hovem, "The Nonlinearity Parameter of Saturated Marine Sediments," Applied Research Laboratories Technical Paper No. 79-17 (ARL-TP-79-17), Applied Research Laboratories, The University of Texas at Austin, revised May 1979.

J. M. Hovem, "Finite Amplitude Effects in Marine Sediments," Applied Research Laboratories Technical Paper 79-41 (ARL-TP-79-41), Applied Research Laboratories, The University of Texas at Austin, June 1979.

J. M. Hovem, "Finite Amplitude Effects in Marine Sediments," Applied Research Laboratories Technical Oral Presentation No. 79-7 (ARL-TO-79-7), Applied Research Laboratories, The University of Texas at Austin, September 1979.

J. M. Hovem, "Viscous Attenuation of Sound in Suspensions and High Porosity Marine Sediments," Applied Research Laboratories Technical Paper No. 79-62 (ARL-TP-79-62), Applied Research Laboratories, The University of Texas at Austin, September 1979.

J. M. Hovem, "Finite Amplitude Effects in Marine Sediments," presented at the Conference on Underwater Applications of Nonlinear Acoustics, University of Bath, Bath, England, September 1979.

J. M. Hovem, "The Nonlinearity Parameter of Saturated Marine Sediments," J. Acoust. Soc. Am. 66, 1463-1467 (1979).

J. M. Hovem, "Viscous Attenuation of Sound in Suspensions and High Porosity Marine Sediments," J. Acoust. Soc. Am. 67, 1559-1563 (1980).

J. M. Hovem and G. D. Ingram, "Viscous Attenuation of Sound in Saturated Sand," Applied Research Laboratories Technical Paper No. 79-35 (ARL-TP-79-35), Applied Research Laboratories, The University of Texas at Austin, April 1979.

J. M. Hovem and G. D. Ingram, "Viscous Attenuation of Sound in Saturated Sand," J. Acoust. Soc. Am. 66, 1807-1812 (1979).

A. C. Kibblewhite, "Attenuation of Underwater Sound of Low Frequencies," Applied Research Laboratories Technical Report No. 76-1 (ARL-TR-76-1), Applied Research Laboratories, The University of Texas at Austin, December 1975.

D. J. Shirley, "Final Report under Contract N00014-70-A-0166, Task 0005," Applied Research Laboratories Technical Report No. 72-6 (ARL-TR-72-6), Applied Research Laboratories, The University of Texas at Austin, January 1972.

D. J. Shirley, "Interim Technical Description of the ARL Compressional Wave In Situ Core Profilometer," Applied Research Laboratories Technical Memorandum No. 74-9 (ARL-TM-74-9), Applied Research Laboratories, The University of Texas at Austin, March 1974.

D. J. Shirley, "Calibration Manual for ARL Profilometer," Informal Memorandum, July 1974.

D. J. Shirley, "Fine Structure of the Sound Speed Profile in Ocean Bottom Sediments from In Situ Measurements," presented at the 89th Meeting of the Acoustical Society of America, Austin, Texas, 8-11 April 1975.

D. J. Shirley, "Transducer for Generation and Detection of Shear Waves," ARL Invention Disclosure, September 1975.

D. J. Shirley, "Determination of the Acoustic Properties of Deep Ocean Sediments from In Situ Profiles," presented at the 92nd Meeting of the Acoustical Society of America, San Diego, California, 16-19 November 1976.

D. J. Shirley, "Method for Measuring In Situ Acoustic Impedance of Marine Sediments," Applied Research Laboratories Technical Paper No. 77-19 (ARL-TP-77-19), Applied Research Laboratories, The University of Texas at Austin, May 1977.

D. J. Shirley, "Acoustic Impedance Measuring Device for Marine Sediments," presented at the 93rd Meeting of the Acoustical Society of America, University Park, Pennsylvania, 6-10 June 1977.

D. J. Shirley, "Laboratory and In Situ Sediment Acoustics," Applied Research Laboratories Technical Report No. 77-46 (ARL-TR-77-46), Applied Research Laboratories, The University of Texas at Austin, August 1977.

D. J. Shirley, "An Improved Shear Wave Transducer," Applied Research Laboratories Technical Paper No. 77-39 (ARL-TP-77-39), Applied Research Laboratories, The University of Texas at Austin, December 1977.

D. J. Shirley, "Method for Measuring In Situ Acoustic Impedance of Marine Sediments," J. Acoust. Soc. Am. 62, 1028-1032 (1977).

D. J. Shirley, "An Improved Shear Wave Transducer," J. Acoust. Soc. Am. 63, 1643-1645 (1978).

D. J. Shirley, "The ARL:UT Subseafloor Environmental Simulator," Applied Research Laboratories Technical Report No. 79-53 (ARL-TR-79-53), Applied Research Laboratories, The University of Texas at Austin, November 1979.

D. J. Shirley, "Acoustical Properties of Sediments," Applied Research Laboratories Technical Report No. 81-20 (ARL-TR-81-20), Applied Research Laboratories, The University of Texas at Austin, May 1981.

D. J. Shirley and A. L. Anderson, "Compressional Wave Profilometer for Deep Water Measurements," Applied Research Laboratories Technical Report No. 74-51 (ARL-TR-74-51), Applied Research Laboratories, The University of Texas at Austin, December 1974.

D. J. Shirley, and A. L. Anderson, "Studies of Sediment Shear Waves, Acoustical Impedance, and Engineering Properties," Applied Research Laboratories Technical Report No. 75-23 (ARL-TR-75-23), Applied Research Laboratories, The University of Texas at Austin, May 1975.

D. J. Shirley and A. L. Anderson, "Acoustic and Engineering Properties of Sediments," Applied Research Laboratories Technical Report No. 75-58 (ARL-TR-75-58), Applied Research Laboratories, The University of Texas at Austin, October 1975.

D. J. Shirley and A. L. Anderson, "In Situ Measurement of Marine Sediment Acoustical Properties During Coring in Deep Water," Applied Research Laboratories Technical Paper No. 75-3 (ARL-TP-75-3), Applied Research Laboratories, The University of Texas at Austin, October 1975.

D. J. Shirley and A. L. Anderson, "In Situ Measurement of Marine Sediment Acoustical Properties During Coring in Deep Water," IEEE Transactions on Geoscience Electronics, Vol. GE-13, No. 4, pp. 163-169, October 1975.

D. J. Shirley and A. L. Anderson, "Experimental Investigation of Shear Waves in Laboratory Sediments," presented at the 90th Meeting of the Acoustical Society of America, San Francisco, California, 3-7 November 1975.

D. J. Shirley and A. L. Anderson, "Shear Waves in Unconsolidated Sediments," presented at the 92nd Meeting of the Acoustical Society of America, San Diego, California, 16-19 November 1976.

D. J. Shirley, A. L. Anderson, and L. D. Hampton, "In Situ Measurement of Sediment Sound Speed During Coring," Applied Research Laboratories Technical Report No. 73-1 (ARL-TR-73-1), Applied Research Laboratories, The University of Texas at Austin, March 1973.

D. J. Shirley, A. L. Anderson, and L. D. Hampton, "Measurement of In Situ Speed During Sediment Coring," OCEAN '73, Record of the International Conference on Engineering in the Ocean Environment, Seattle, Washington, 25-28 September 1973.

D. J. Shirley, A. Bedford, and S. K. Mitchell, "Wave Propagation in a Saturated Model Sediment with Varied Liquid Properties," Submitted to J. Acoust. Soc. Am. (1982).

D. J. Shirley and D. W. Bell, "Acoustics of In Situ and Laboratory Sediments," Applied Research Laboratories Technical Report No. 78-36 (ARL-TR-78-36), Applied Research Laboratories, The University of Texas at Austin, August 1978.

D. J. Shirley and D. W. Bell, "Temperature Variation of the Acoustic Properties of Laboratory Sediments," presented at the 98th Meeting of the Acoustical Society of America, Salt Lake City, Utah, November 1979.

D. J. Shirley, D. W. Bell and J. M. Hovem, "Laboratory and Field Studies of Sediment Acoustics," Applied Research Laboratories Technical Report No. 79-26 (ARL-TR-79-26), Applied Research Laboratories, The University of Texas at Austin, June 1979.

D. J. Shirley and L. D. Hampton, "Acoustic Velocity Profilometer for Sediment Cores," OCEAN "72, Record of the International Conference on Engineering in the Ocean Environment, Newport, Rhode Island, 13-15 September 1972.

D. J. Shirley and L. D. Hampton, "Determination of Sound Speed in Cored Sediments," Applied Research Laboratories Technical Report No. 72-44 (ARL-TR-72-44), Applied Research Laboratories, The University of Texas at Austin, December 1972.

D. J. Shirley and L. D. Hampton, "Acoustic Velocimeter for Ocean Bottoms Coring Apparatus," ARL Invention Disclosure, November 1973.

D. J. Shirley and L. D. Hampton, "Shear Wave Measurements in Laboratory Sediments," Applied Research Laboratories Technical Paper No. 77-31 (ARL-TP-77-31), Applied Research Laboratories, The University of Texas at Austin, August 1977.

D. J. Shirley and L. D. Hampton, "Shear Wave Measurements in Laboratory Sediments," J. Acoust. Soc. Am. 63, 607-613 (1978).

D. J. Shirley, J. M. Hovem, G. D. Ingram, and D. W. Bell, "Sediment Acoustics," Applied Research Laboratories Technical Report No. 80-17 (ARL-TR-80-17), Applied Research Laboratories, The University of Texas at Austin, April 1980.

K. H. Stokoe (UT Austin), D. G. Anderson (Fugro, Inc.), E. J. Arnold (UT Austin), R. J. Hoar (UT Austin), and D. J. Shirley, "Development of a Bottom Hole Device for Offshore Shear Wave Velocity Measurement," Proceedings of the 10th Annual Offshore Technology Conference, Houston, Texas, 8-11 May 1978.

B. E. Tucholke (Lamont-Doherty Goelogical Observatory, Columbia University) and D. J. Shirley, "Comparison of Laboratory and In Situ Compressional-Wave Velocity Measurements on Sediment Cores from the Western North Atlantic," Journal of Geophysical Research, 84, 687-695 (1979).

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