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STUDIES OF SEDIMENT SHEAR WAVES, ACOUSTICAL IMPEDANCE, AND ENGINEERING PROPERTIES

Donald J. Shirley, et al

Texas University

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7 May 1975

THE UNIVERSITY OF TEXAS AT AUSTIN

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STUDIES OF SEDIMENT SHEAR WAVES, ACOUSTICAL IMPEDANCE, AND ENGINEERING PROPERTIES

Donald J. Shirley
Aubrey L. Anderson

OFFICE OF NAVAL RESEARCH
Contract N00014-70-A-0166, Task 0017

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Compressional wave speed and attenuation have been measured in situ with the ARL/UT compressional wave profilometer. As an extension of this work, studies have been made of the feasibility of measuring shear wave speed and attenuation, as well as sediment bulk density in situ, using similar techniques. Various transducer configurations have been constructed and tested. Preliminary data have been measured using some of the transducers. Concurrent measurements of engineering properties enable comparisons to be made with acoustic properties. Instruments have been contructed to measure several sediment engineering (over)

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ABSTRACT

Compressional wave speed and attenuation have been measured in situ with the ARL/UT compressional wave profilometer. As an extension of this work, studies have been made of the feasibility of measuring shear wave speed and attenuation, as well as sediment bulk density in situ, using similar techniques. Various transducer configurations have been constructed and tested. Preliminary data have been measured using some of the transducers. Concurrent measurements of engineering properties enable comparisons to be made with acoustic properties. Instruments have been constructed to measure several sediment engineering parameters including Atterberg limits and vane shear strength.

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I. INTRODUCTION

There are quite often uncertainties involved in the determination of acoustic and engineering properties of samples removed from the ocean bottom and brought to the surface, due to disturbances inherent in sampling and recovery. As a result, attempts have been made to measure sediment properties in situ. Such work has been reported by Hamilton (1963), Bennin and Clay (1967), Lewis et al. (1970), Inderbitzen et al. (1971), and Allman (1974). Most of the work reported has been limited to shallow penetration of the ocean bottom. However, sampling by coring has been done to 40 m, so in situ measurements to the same depths as core penetration are desirable.

An instrument capable of measuring compressional wave sound speed and attenuation has been constructed and tested at Applied Research Laboratories (ARL), The University of Texas at Austin. The instrument, designated the ARL compressional wave sound speed profilometer, is designed for attachment to existing corers and derives a profile of sound speed and attenuation during the process of taking a core. Preliminary data have been reported by Shirley and Anderson (1974) for cores taken in the Atlantic Ocean in water depths to 4.5 km and bottom penetrations to 12 m.

Complete characterization of sediment viscoelastic parameters requires at least five acoustic measurements. These include compressional wave speed (c_p) and attenuation (α_p) shear wave speed (c_s) and attenuation (α_s), and acoustic impedance (ρc_p).

With the successful use of the compressional wave profilometer, work was started in August 1974 to examine the feasibility of measuring the other three viscoelastic parameters in situ using methods similar to the compressional wave determinations. With sponsorship from the Office of Naval Research (ONR) under Contract N00014-70-A-0166, Item 0017, work has progressed on the following tasks.

1. Measurement of shear wave speed and attenuation in sediments. This includes evaluation of circuit and transducer types and configurations to optimize the in situ measurement.

2. Acoustical measurement of sediment bulk density by impedance measurements. Sensitivity of electrical parameters of a driven transducer to sediment acoustical impedance for various transducer configurations will be measured in order to determine the feasibility of in situ acoustical measurement of bulk density.

3. Study of the correlation between the corer deceleration profile and sediment strength parameters. This will allow use of the available accelerometer record to determine sediment engineering properties in situ.

4. Concurrent measurements of acoustical and engineering properties of sediments to investigate useful correlations between the two. This will allow use of the profilometer acoustical data to determine sediment engineering properties in situ.

Because of the problems associated with designing and constructing transducers to make shear wave measurements, the main thrust of the work to date has been in this area. Five different types of transducers have been constructed and evaluated using both solid media (lucite and aluminum) and laboratory sediments.

Transducers and electronic circuitry have been constructed for measuring the acoustic impedance of a sediment through the effects upon the Q and resonance frequency of a driven ceramic transducer element. Preliminary measurements show a linear relationship between phase changes in the driving voltage and current waveforms, and measured values of sediment acoustic impedance.

Investigation of correlations between acoustical and engineering properties has progressed to the point of construction of some of the equipment to make measurements of the various engineering properties, but as yet no dynamic measurements have been made.

II. TRANSDUCERS

A shear transducer must generate a shearing motion and couple this motion into the medium. Figure 1 illustrates one method of generating a shear wave which was utilized in the first two types of transducers that were built. If an electric field is applied to a piezoelectric ceramic perpendicular to its direction of electrical polarization, the ceramic will be deformed in a manner illustrated by the dotted lines in Fig. 1. If the electric field is reversed, the direction of deformation is also reversed so that the top face of the ceramic block will experience a shearing motion with the application of an electrical signal to the electrodes.

Types A and B transducers were built using the design of Fig. 1. Type A transducer had dimensions of 1 x 3/4 x 1/4 in. with the smallest dimension in the direction of polarization and wave propagation. Type B was similar except that the dimensions were 1 x 1 x 1 in. All types of the transducers were constructed in pairs for evaluation and use.

To evaluate and compare performance of the various types of transducers, it was necessary to select an appropriate medium. A lucite rod 2 in. in diameter was selected since the transducer elements could be cemented to the ends for maximum coupling and the expected shear wave speed was low enough that the length could be a reasonable dimension. None of these factors was available in any type of sediment. Aluminum, stainless steel, and polyethylene were also tried but were abandoned because of unsuitable properties. The metals were heavy and had high shear wave speeds, requiring a longer length; the polyethylene could not be cemented with epoxy.

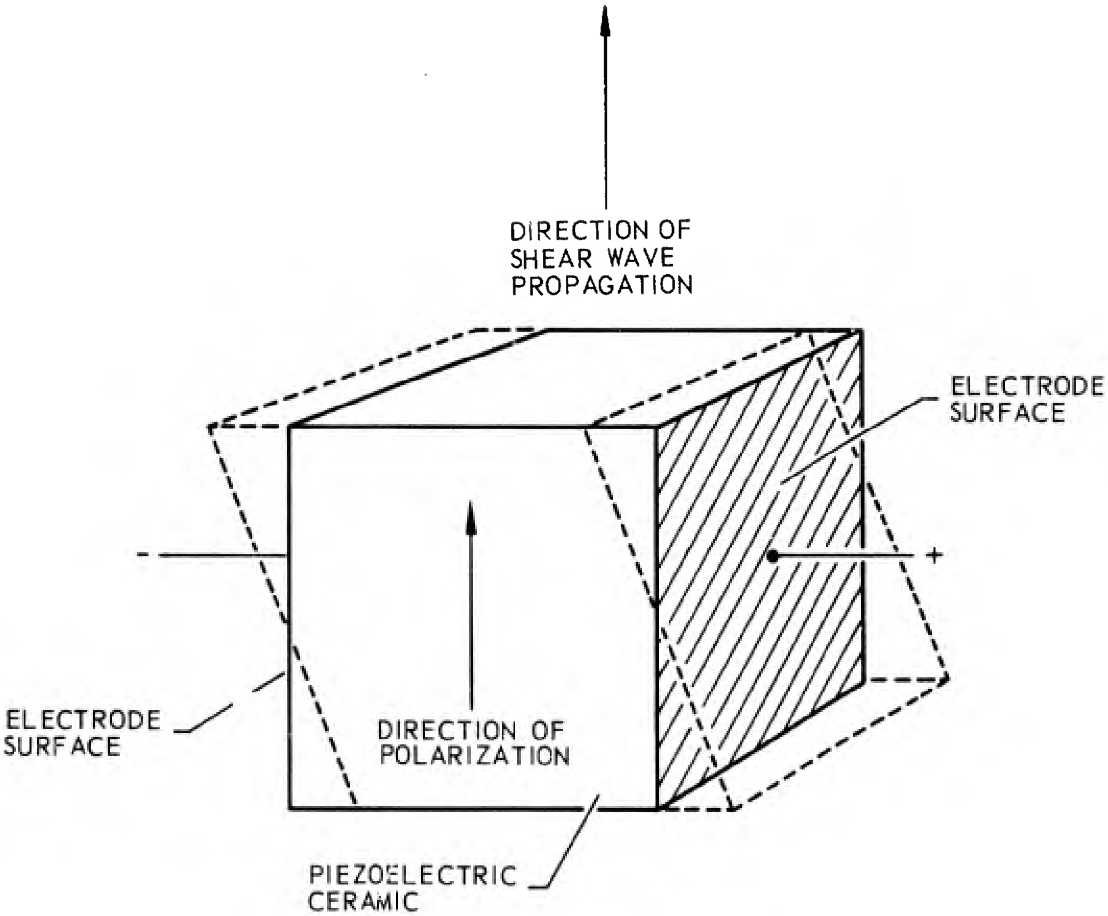


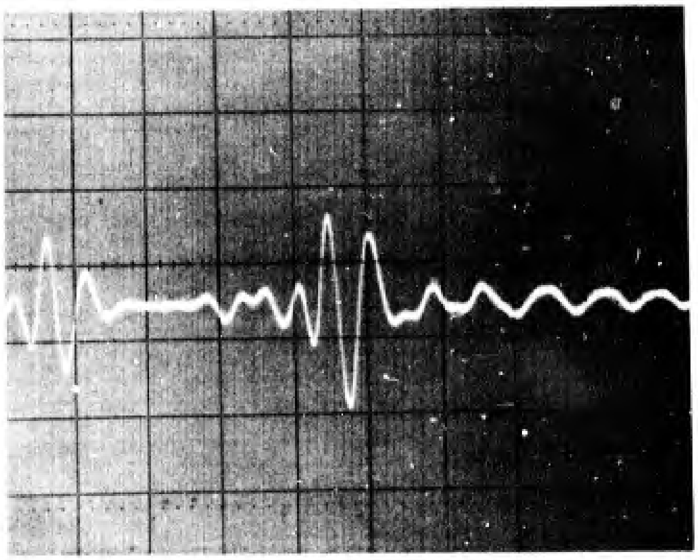
FIGURE 1
SHEAR WAVE TRANSDUCER

ARL - UT
AS-75-473
DJS - DR
4 - 3 - 75

Figure 2 shows an oscilloscope photograph of the shear wave pulses propagating on a lucite rod 1.03 m in length using the type A transducers. The first pulse on the trace is the electrical feedover of the transmit pulse between projector and receiver. The second pulse is the shear wave pulse propagated down the lucite rod. This figure also demonstrates one of the problems associated with the generation of shear waves by this method. The shearing action induced in the ceramic material by the electrical signal also tends to change the thickness dimension in the direction of polarization, effectively generating a compressional wave of some amplitude. The compressional wave can be seen in Fig. 2 as a precurser, which interferes with the start of the shear wave pulse.

If the time difference between the highest positive peak in the electrical feedover and the highest positive peak in the received pulse is measured, a shear wave sound speed of 1320 m/sec can be calculated. This value is within 4% of the reported (Press, 1966) value for lucite of 1276 m/sec.

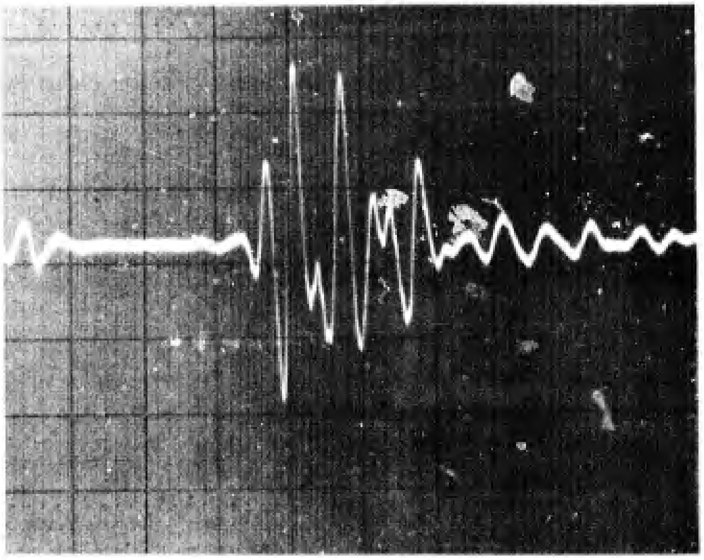
Figure 3 shows oscilloscope photographs of shear wave propagation through a 0.98 m lucite rod using the type B transducers. The fact that shear waves are linearly polarized was used to demonstrate that the propagated pulses were indeed shear waves as illustrated in this figure, where the top trace shows the received pulse with projector and receiver transducers oriented parallel to each other, and the bottom trace shows a 17.5 dB decrease in amplitude when the transducers are oriented perpendicularly. Notice also that with the changed dimensions using the same type ceramic ($BaTiO_3$-channelite 300), there is a 30.8 dB increase in amplitude from type A to type B. Again the exact timing of the start of the received pulse is obscured by the preceding compressional wave, but using the time difference between the first positive peak in the electrical feedover pulse and the first negative peak in the received pulse and a travel path of 0.98 m, a shear wave sound speed of 1380 m/sec is calculated.



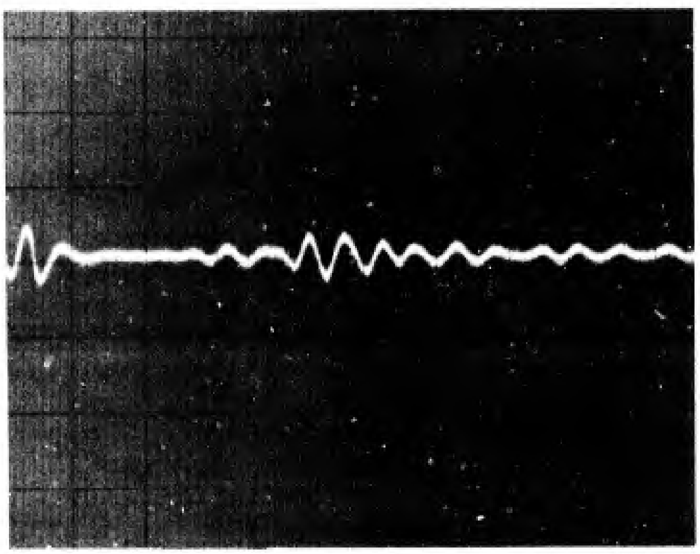
VERTICAL SCALE: 0.01 V/div
HORIZONTAL SCALE: 0.2 msec/div
PREAMPLIFIER GAIN: 40 dB
FREQUENCY: 10 kHz

FIGURE 2
SHEAR WAVE PROPAGATION IN LUCITE
TYPE A TRANSDUCER

ARL - UT
AS-75-474
DJS - DR
4 - 3 - 75



TRANSDUCERS PARALLEL



TRANSDUCERS PERPENDICULAR

VERTICAL SCALE: 0.2 V/div
HORIZONTAL SCALE: 0.2 msec/div
PREAMPLIFIER GAIN: 40 dB
FREQUENCY: 10 kHz

FIGURE 3
SHEAR WAVE PROPAGATION IN LUCITE
TYPE B TRANSDUCER

ARL - UT
AS-75-475
DJS - DR
4 - 3 - 75

In an attempt to further increase the shear wave output of the projector and the receiver sensitivity, a different method of shear wave generation was investigated. Figure 4 shows a schematic representation of this transducer type, designated type C. The transducer consists of a ceramic element vibrating in the extensional mode as indicated by the arrows. Each end of the ceramic element is cemented to a metal angle such that the metal angle is driven in a shearing mode along the face perpendicular to that cemented to the ceramic. The face of the metal angle thus radiates a shear wave into the medium in contact with it. The corprene is a cork-neoprene compound used for acoustically isolating the back of the metal angle from the ceramic. The ceramic element consists of six layers of ceramic with electroded faces parallel to the polarization so they vibrate in the thickness mode and are arranged to be electrically driven in parallel to reduce the transducer electrical impedance. Another effect of building an element in layers is that the driver electrodes can be shielded by the grounded electrodes and thus reduce electrical feedover.

Figure 5 shows oscilloscope photographs of propagation along a 0.98 m lucite rod using the type C transducers. Due to the manner of constructing the ceramic element, the electrical feedover pulse at the beginning of the traces is too small to be detected. The increase in amplitude between this type transducer and the type B is 28 dB and between it and type A, 59 dB. However there is also an increase in the ratio between compressional wave and shear wave generation as is seen by comparing the two traces of Fig. 5. Upon rotation of 90° between transducer orientation, the shear wave pulse is greatly decreased leaving only the compressional wave pulse, which is not affected by transducer orientation. The difference between compressional wave generation and shear wave generation is only 10.7 dB for this transducer type.

The next type of transducer to be designed is illustrated in Fig. 6 and is designated type D. It is similar in operation to

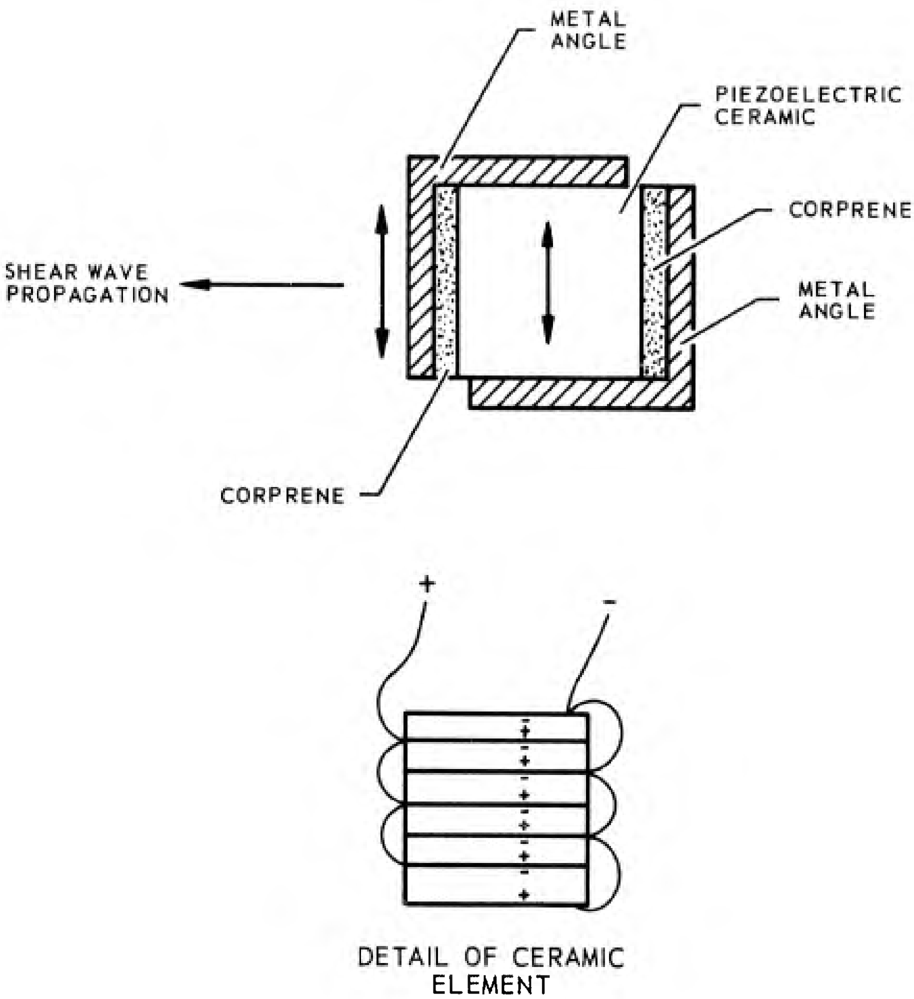


FIGURE 4
SHEAR WAVE TRANSDUCER
TYPE C

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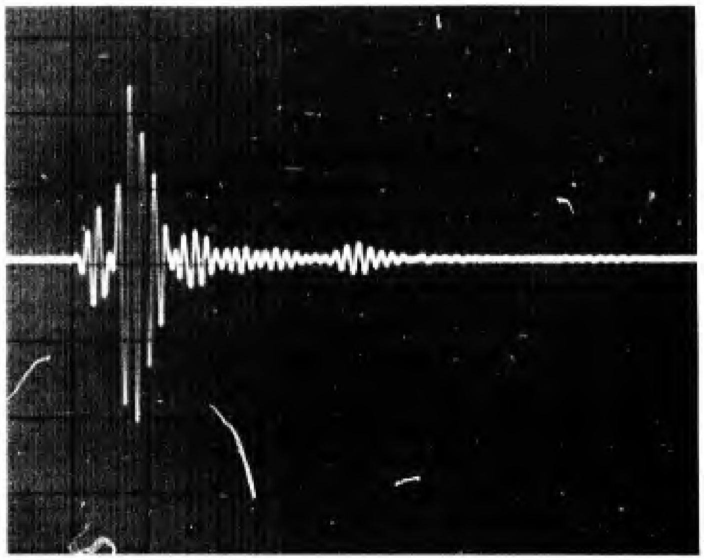
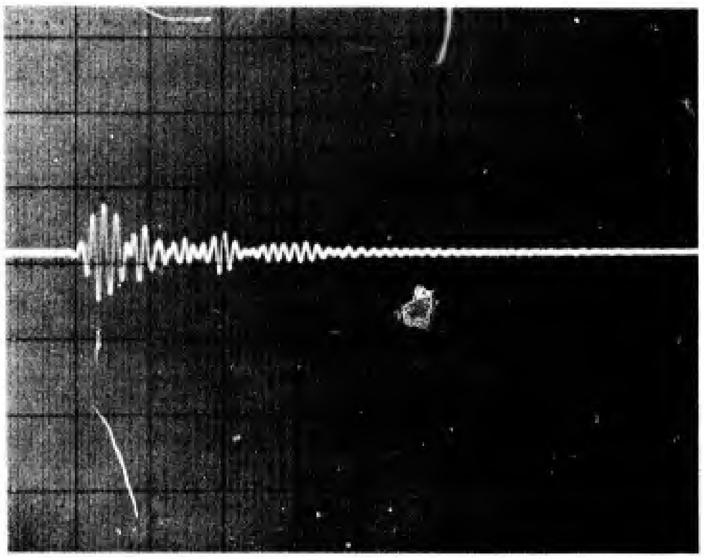
DJS - DR
4 - 3 - 75



TRANSDUCERS PARALLEL



TRANSDUCERS PERPENDICULAR

VERTICAL SCALE: 0.5 V/div
HORIZONTAL SCALE: 0.5 msec/div
PREAMPLIFIER GAIN: 20 dB
FREQUENCY: 11 kHz

FIGURE 5
SHEAR WAVE PROPAGATION IN LUCITE
TYPE C TRANSDUCER

ARL - UT
AS-75-477
DJS - DR
4 - 3 - 75

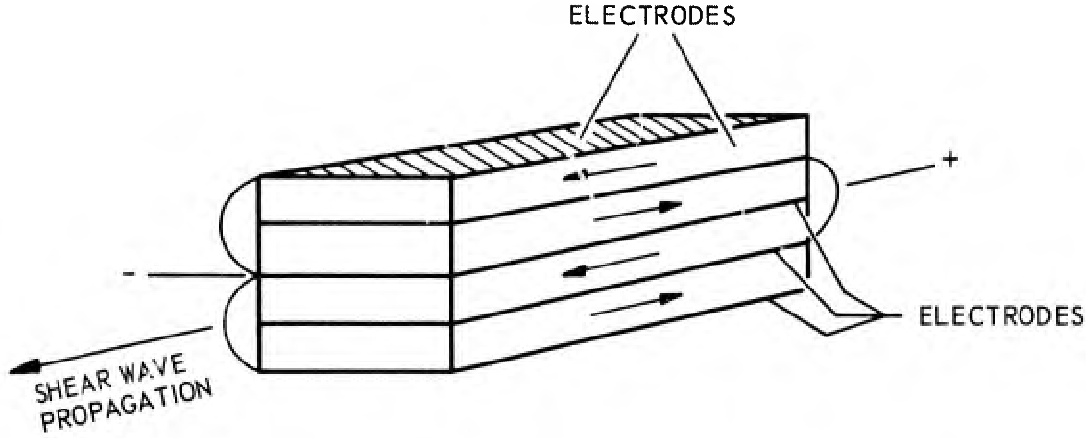


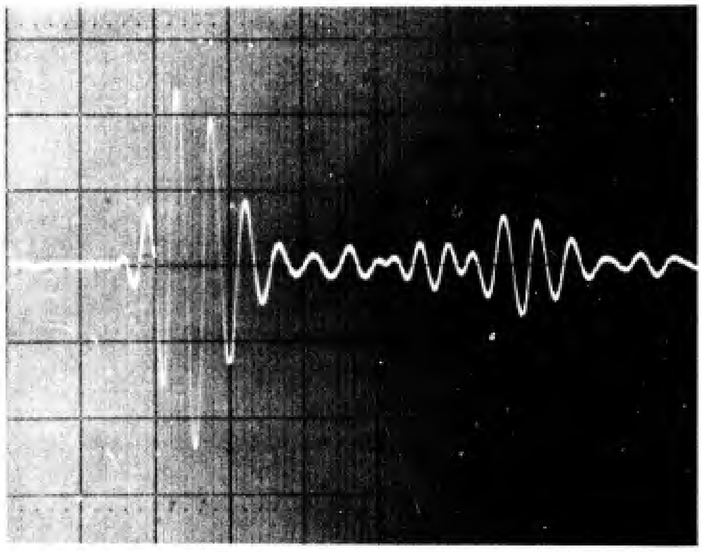
FIGURE 6
SHEAR WAVE TRANSDUCER
TYPE D

ARL - UT
AS-75-478
DJS - DR
4 - 3 - 75

types A and B except that, instead of being a solid block of ceramic, it is composed of four layers of ceramic. The polarization of each layer is alternated as shown by arrows in the diagram of Fig. 6. Metal electrodes are sandwiched between the ceramic layers and connected as shown. The layers are thus driven in parallel with the shear motion of all the layers adding constructively. Again, as in the type C transducer, the grounded electrodes shield the hot electrodes and thus reduce electrical feedover of the transmitted pulse between projector and receiver. The size of the elements is 1/2 x 1/2 x 1 in. with the longest dimension in the direction of propagation.

Figure 7 shows an oscilloscope photograph of the propagation of shear waves in the 0.98 m long lucite rod using the type D transducers. This type transducer far exceeds all the other types tested for amplitude response and suppression of compressional waves. Resonance frequency of this element is 3.5 kHz. The amplitude response is 65.7 dB over that of the type A transducers, 34.5 dB over type B, and 6.6 dB over that of type C. No compressional wave could be observed with this transducer design except when the electroded faces of the element were in contact with the lucite rod. This mode produced a compressional wave pulse measuring 23.8 dB below that of the shear wave pulse measured with the proper driving force of the element in contact with the rod.

One other type of transducer has been built, copied from a design by Barabaros Celikkol. This design is illustrated in Fig. 8 and is designated type E. The design incorporates a piezoelectric ceramic layered element similar to that used in the type C transducers. The element is cemented to a backup mass made from a 2 in. length of 7/8 in. diam brass rod; a 1/2 x 1/2 x 3 in. aluminum angle is cemented to the other face of the element. The extensional vibration of the element thus drives the end of the aluminum angle, causing it to move longitudinally. Thus, the two faces of the aluminum angle radiate a shear wave at right angles to the motion of the element and aluminum angle. This type of transducer is not easily cemented to the lucite



VERTICAL SCALE: 1 V/div
HORIZONTAL SCALE: 0.5 msec/div
PREAMPLIFIER GAIN: 20 dB
FREQUENCY: 4 kHz

FIGURE 7
SHEAR WAVE PROPAGATION IN LUCITE
TYPE D TRANSDUCER

ARL - UT
AS-75-479
DJS - DR
4 - 3 - 75

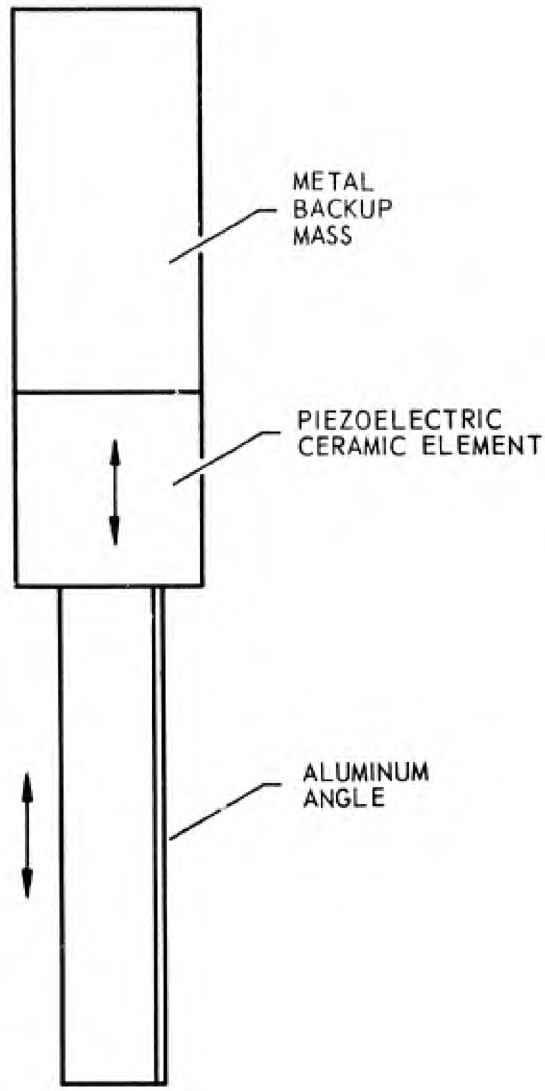


FIGURE 8
SHEAR WAVE TRANSDUCER
TYPE E

ARL - UT
AS-75-480
DJS - DR
4 - 3 - 75

rod and so could not be compared to the other transducer configurations. However, in tests in dry sand, the output appeared to be equivalent to that of the type B transducers. Usefulness of this transducer was limited because of compressional wave interference through the holder which was used to rigidly mount the transducers together. Since this type transducer could not be used in a corer, no further effort was made to decrease the compressional wave generation.

III. MEASUREMENTS

Although the lucite rod provides a convenient medium for comparison of shear wave transducers, it does not provide a realistic view of the problems associated with propagation of shear waves in a sediment. For this reason, several laboratory type sediments were made for testing and evaluating the various shear wave transducers. The most common and easily obtainable sediment ingredients available were sand and kaolinite clay. The sand is a rounded quartz beach sand obtained from Panama City, Florida. The mean grain size of this sand was 1 1/2 φ with a dry bulk density of 1.56 g/cm^3. When saturated with water, it has a wet bulk density of 1.95 g/cm^3 and has 25.6% water.

Shear wave speeds and attenuations were measured in the sand both dry and water saturated. Results are tabulated in Table I for all of the five transducer types. Sound speed and attenuation were measured by burying the transducer sets in the sand, determining time delay and amplitude of the received pulse, and then changing the transducer spacing and reburying for another measurement. Three to eight different spacings were used for each determination, depending on the transducer and its sensitivity. The values given in Table I are averages over all the data points for each determination. Data points for time delay were plotted and a best fit straight line was drawn through the data points. The slope of this line is the sound speed. Attenuation data were handled in a similar manner with each data point corrected for spreading loss. Reference to Table I shows that types A, B, and D transducers gave similar results, while types C and E are very dissimilar. The rather high value of sound speed given by the type C transducer could possibly be due to a compressional wave being measured instead of a shear wave, since the transducers could not be used in the water saturated sediment due to swamping by compressional waves transmitted through the wet sand. Type E transducers also could not be used in water saturated sand due to compressional waves.

TABLE I

COMPARISON OF SHEAR WAVE SPEED AND ATTENUATION USING VARIOUS TYPES OF TRANSDUCERS

Transducer Type	Sound Speed		Attenuation Coefficient	
	Wet	Dry	Wet	Dry
A	69 m/sec	168 m/sec	400 dB/m	65 dB/m
B	69 m/sec	178 m/sec	180 dB/m	50 dB/m
C		330 m/sec		45 dB/m
D	68 m/sec	194 m/sec	33 dB/m	57 dB/m
E		143 m/sec		138 dB/m

The sound speed measurements in wet sand agree closely between the three types of transducers used while the attenuation coefficients measured fluctuate wildly. It was found that the amplitude of the received pulse was very sensitive to positioning of the transducers in the sediment due to changes in coupling between transducer and sediment. Since each measurement required that the transducers be unburied, have their spacing changed, and then be reburied, it is unlikely that the transducers could be replaced in exactly the same way, thus precluding an accurate measurement of attenuation. Dry sand behaved somewhat like the wet sand except that the sound speed was also somewhat sensitive to changes in the medium. Care was taken to settle the sand around the transducers, by tapping, and straight line plots were finally obtained for the dry sand. Figures 9 and 10 show data point plots for sound speed and attenuation using type D transducers in both wet and dry sand.

Since the measurements described above indicated a sensitivity to pressure on the sand medium, measurements were made to determine this sensitivity. Figure 11 illustrates the apparatus used for these measurements. A lightweight aluminum tube filled with the medium under test is plugged at each end with the transducers in housings of the proper diameter so as to allow freedom for the transducer to slide into the tube to compress the sand. The tube and transducers are held rigidly in a frame so that the force exerted on one of the transducers by a jack screw is measured at the other end by a strain gauge load cell. Inside diameter of the tube is 5.4 cm and two lengths of tube are used, one measuring 36 cm in length and the other 20 cm. Sound speed and attenuation are calculated as a function of the pressure exerted on the sand by using the time delay and amplitude differences measured in each of the two lengths of tube. Figures 12 and 13 show sound speed and attenuation, respectively, versus unidirectional frame pressure for both wet and dry sand. The wet sand contained 17.7% water after the measurements were completed. As expected, the effect of frame pressure is nonlinear and has the greatest effect at small pressures

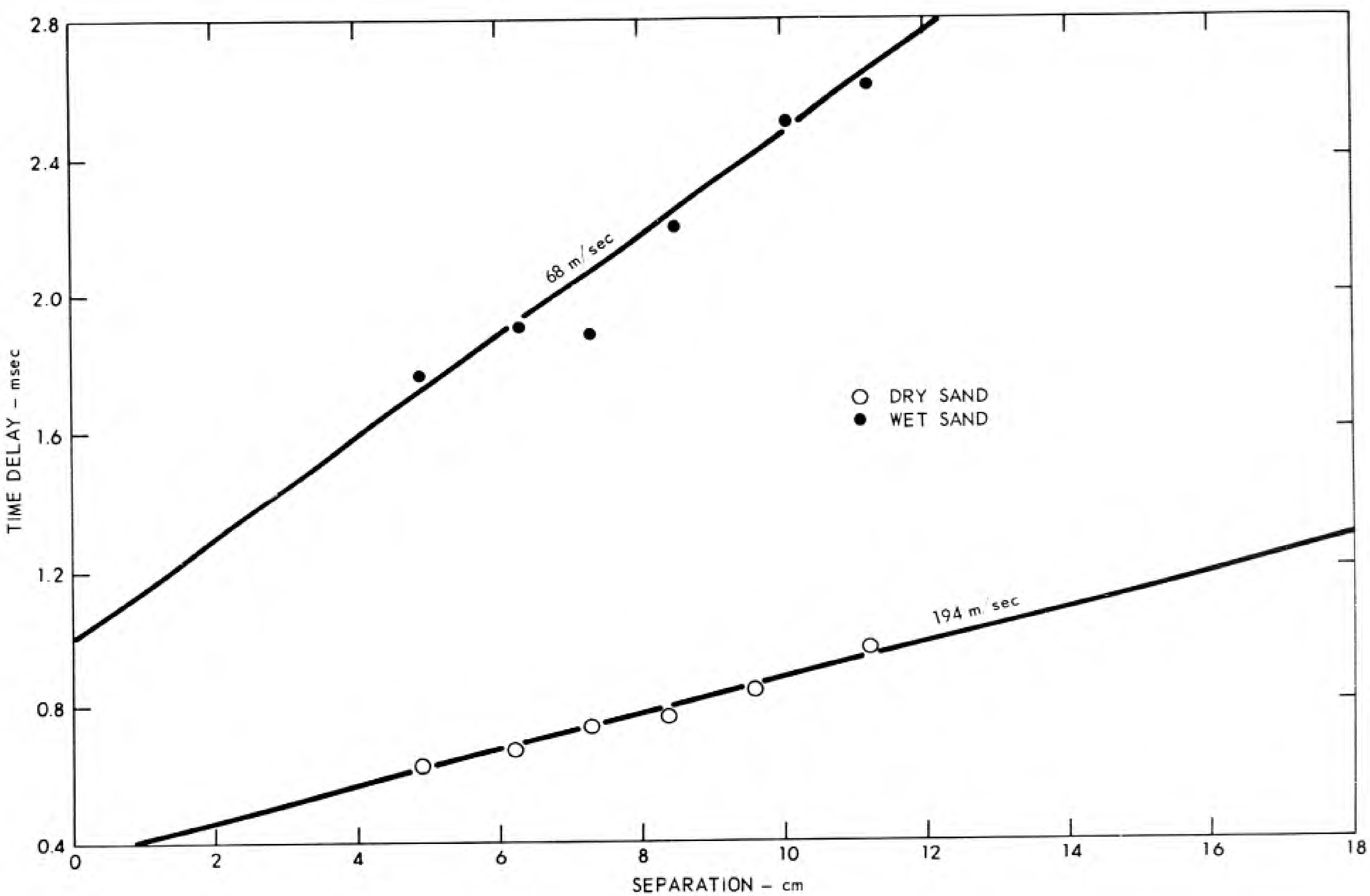


FIGURE 9
SHEAR WAVE SPEED MEASUREMENT IN BEACH SAND

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AS-75-481
DJS - DR
4 - 3 - "

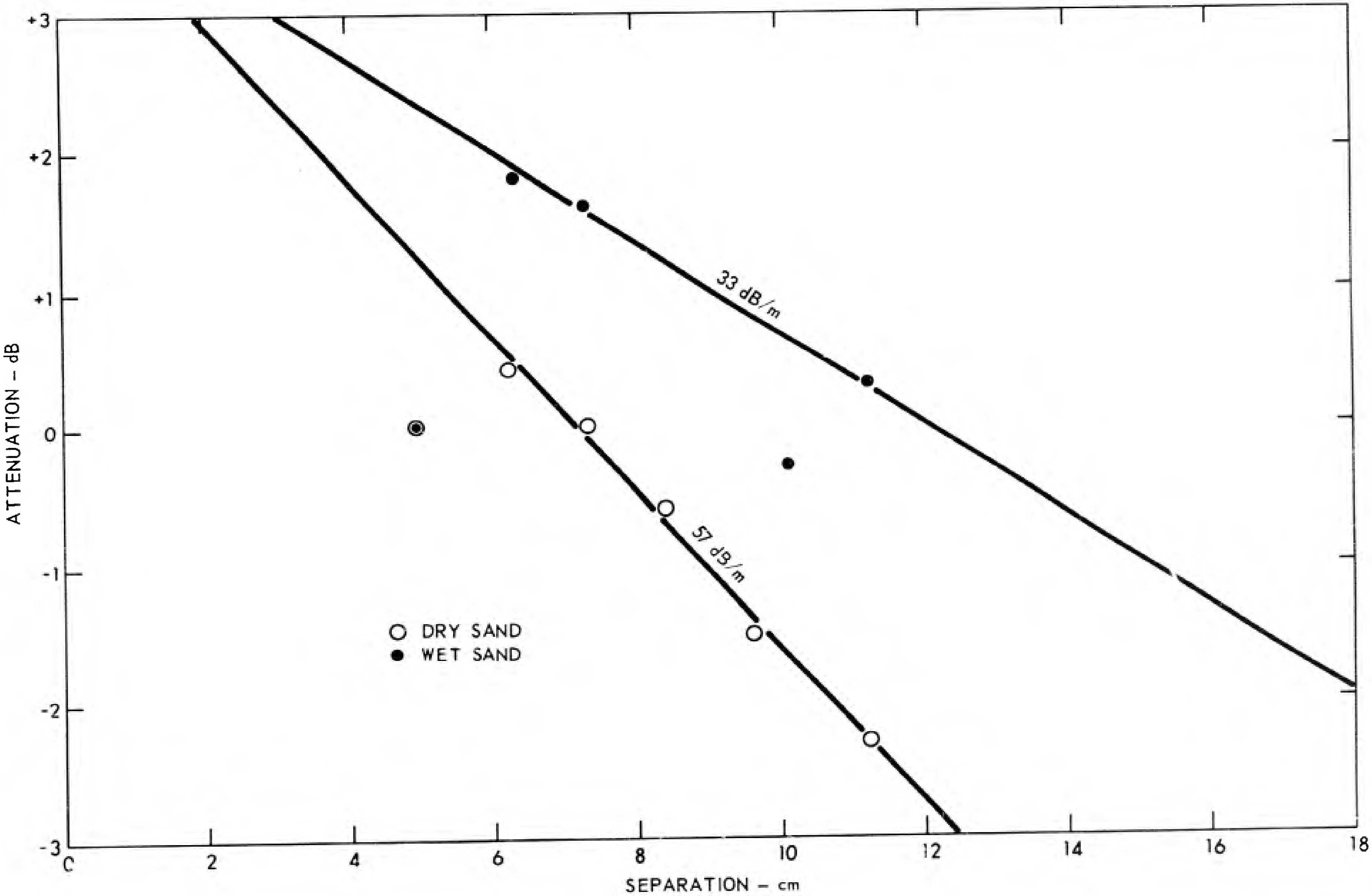


FIGURE 10
SHEAR WAVE ATTENUATION MEASUREMENT IN BEACH SAND

ARL - UT
AS-75-482
DJS - DR
4 - 3 - 75

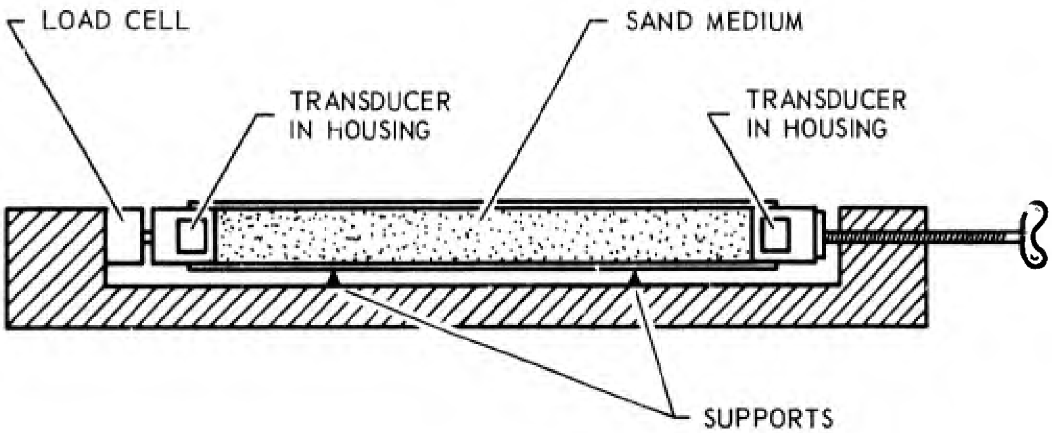


FIGURE 11
APPARATUS FOR MEASUREMENT OF SOUND SPEED
AND ATTENUATION VERSUS FRAME PRESSURE

ARL - UT
AS-75-483
DJS - DR
4 - 3 - 75

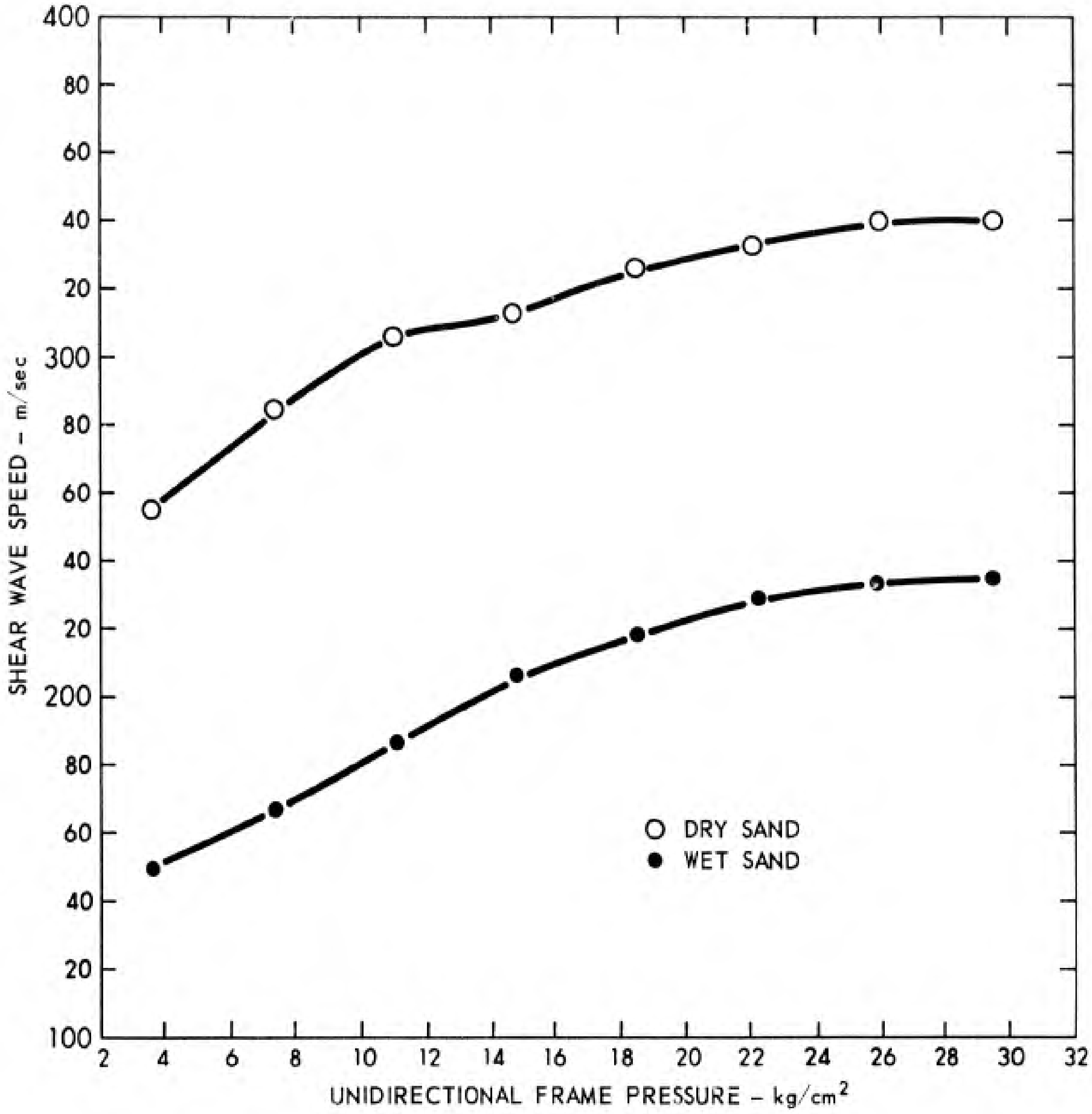


FIGURE 12
SHEAR WAVE SPEED IN BEACH SAND VERSUS FRAME PRESSURE

ARL - UT
AS-75-484
DJS - DR
4 - 3 - 75

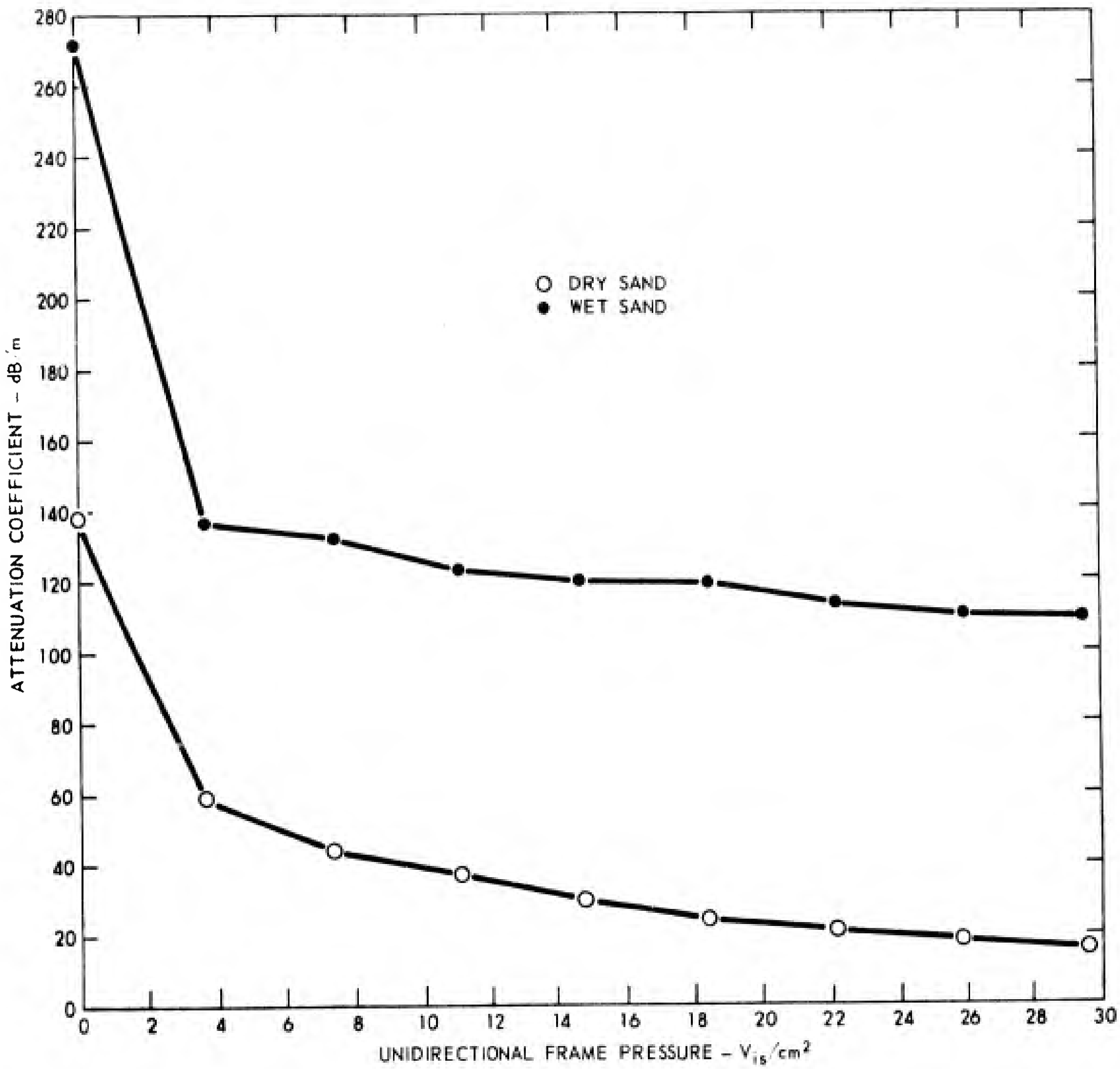


FIGURE 13
SHEAR WAVE ATTENUATION IN BEACH SAND VERSUS FRAME PRESSURE

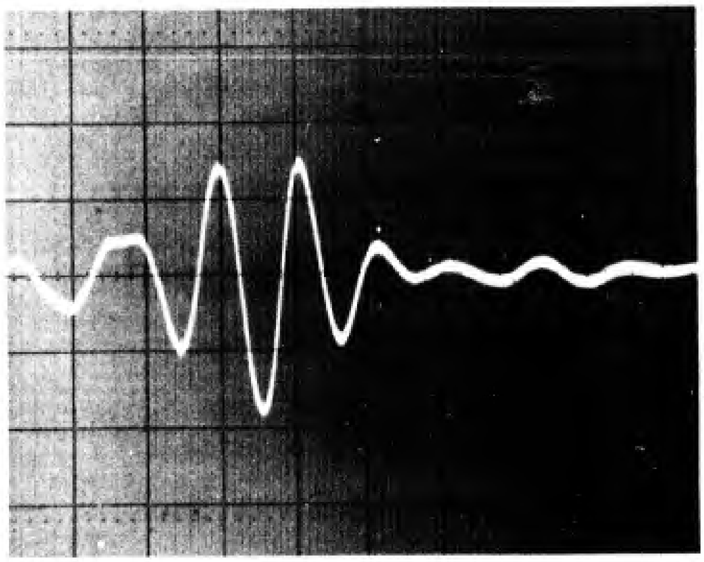
ARL - UT
AS-75-485
DJS - DR
4 - 3 - 75

such as encountered in the measurement of sound speed and attenuation by burying the transducers in sand where the only frame pressure exerted is the overburden of a few centimeters of sand.

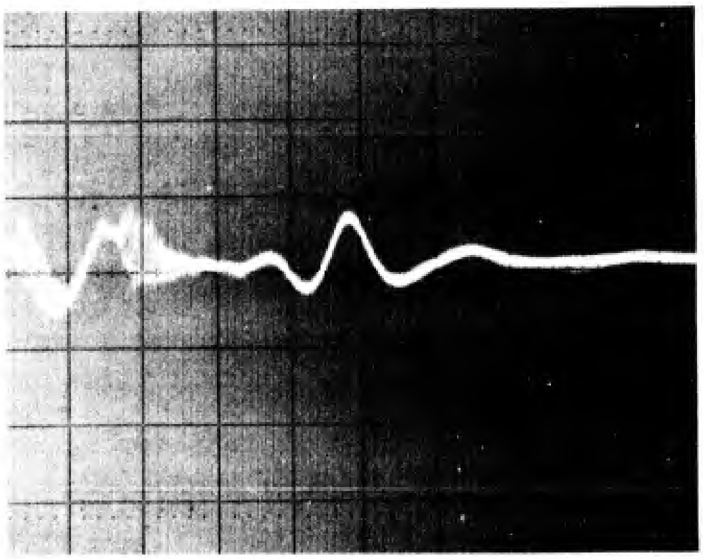
While the sound speed and attenuation measurements were being made in the Panama City, Florida, sand, concurrent measurements were being made in other sediment types.

One measurement was made on a compacted garden soil. The soil was was compacted in a tube 5.4 cm i.d. to form a cylinder 7.6 cm in length. The tube was removed and the type B transducers clamped to the ends of the sediment plug. A shear wave sound speed of 282 m/sec was measured. The bulk density of the compacted soil was 2.34 g/cm^3 and water content was 14.9%.

Another measurement was also made using the type D transducers mounted in a cutter designed for use with the Lamont-Doherty Geological Observatory corer. The type D transducer elements were the only ones with a size appropriate for mounting in the transducer holders designed for attachment to ocean bottom corers (for use with the ARL compressional wave sound speed profilometer). This transducer arrangement is one that would be used for in situ measurements. The cutter head was inserted into the dry beach sand, the water saturated beach sand, and a very fine silty sand obtained from a gravel washing operation. Figure 14 shows oscilloscope photographs of the received signals in the beach sand. Both traces show a 1 cycle pulse from electrical feedover. In the trace for wet sand there are also, at the beginning of the trace, two pulses of high frequency energy which are compressional wave pulses generated at the onset and finish of the transmit pulse and are propagated at a relatively higher velocity than the shear wave. Frequency of the compressional waves is approximately 90 kHz. Absence of waves in the dry sand is due to higher attenuation for compressional waves. Table II lists the results of this series of



DRY BEACH SAND



WATER SATURATED BEACH SAND

VERTICAL SCALE: 0.05 V/div
HORIZONTAL SCALE: 0.2 msec/div
FREQUENCY: 3.5 kHz

FIGURE 14
SHEAR WAVE PROPAGATION IN BEACH SAND

ARL - UT
AS-75-486
DJS - DR
4 - 3 - 7?

TABLE II

SOUND SPEED AND ATTENUATION FOR THREE SEDIMENTS
USING TYPE D TRANSDUCERS

Sediment Type	Sound Speed	Attenuation	Calculated Dynamic Shear Modulus
Dry Beach Sand	213 m/sec	54 dB/m	$5.05\times10^{8}\ \frac{dynes}{cm^2}$
Water Saturated Beach Sand	81 m/sec	272 dB/m	$9.28\times10^{7}\ \frac{dynes}{cm^2}$
Water Saturated Silty Sand	42 m/sec	563 dB/m	$3.07\times10^{7}\ \frac{dynes}{cm^2}$

measurements for both sound speed and attenuation coefficients. Attenuation coefficients were calculated using the average value previously determined for dry beach sand, and then using the decrease in signal level in the other two sediments to calculate their attenuation coefficients. This method is based on the assumption that coupling from the transducers into each of the three sediments is the same. This assumption is as yet untested. The discrepancy between the sound speed values in Table I and those in Table II is probably due to the difficulty in determining the exact time delay of the received pulse. The values in Table I were derived by changing the transducer spacing in steps and measuring the time delay to a particular feature of the received pulse, plotting these time delays versus transducer spacing, then fitting a straight line to these points. The slope of this line is then the sound speed. This type of measurement could not be done for the data of Table II because the transducers are rigidly mounted in a hollow metal cylinder.

Overall the type D transducers have been shown to be the best configuration of all the types tested, being much more efficient and sensitive and having less compressional wave generation than any of the others. Measurements are proceeding using only this transducer type.

IV. PROJECTED MEASUREMENTS

Due to the low efficiency and sensitivity of all the transducers prior to construction of the type D elements, measurements of shear wave sound speed and attenuation on the clay type sediments had failed because of the low shear modulus inherent in freshly prepared laboratory clay sediments. Measurements in the fine silty sand were near the limit of the type D transducer capabilities. Using the 39 m/sec sound speed measured and a value of wet bulk density of 2.02 g/cm^3 measured for the sediment, a shear modulus of 3.07×10^7 $dynes/cm^2$ is calculated. Table III shows expected values of shear modulus for several types of sediments. Values for freshly mixed laboratory clays are obviously too low for the present transducer capabilities. However the natural sediments are all seen to lie within the range of this transducer type.

Future work with the shear wave transducers will include measurements on sand-clay mixtures and on laboratory clay sediments which have been unsaturated either by draining or evaporating some of the pore water to increase the shear modulus.

There is an indication that coupling between the transducer face and the sediment is a large factor in efficiency and sensitivity of the transducer measurements. Measurements will be made to determine if a rough or corrugated transducer face would increase the coupling.

Indications are that constructing the transducer elements out of thin layers also increases the efficiency of the element. A new set of elements is being constructed using more and thinner layers to test this effect.

TABLE III

Dynamic Shear Modulus of Sediments
(After Anderson, 1974)

Material	Modulus, G dynes/cm^2
Freshly mixed laboratory clay water sediments	$10^5 - 10^6$
Natural, in-place slough and harbor muds	$10^6 - 10^8$
Natural, in-place ocean bottom clays	$10^8 - 10^9$
Natural, in-place ocean silts and sands	$10^9 - 5 \times 10^9$ maximum for fine sand

Since measurements can be made rather easily in a sand sediment due to its high shear modulus, these measurements will continue to be made using various types of sand with different grain characteristics.

V. ACOUSTIC IMPEDANCE

The characteristics of an electomechanical transducer are such that if the radiation loading on a driven element is changea by a change in the acoustic impedance of the medium into which the transducer radiates, the Q and resonance frequency of the transducer will change. At points near resonance, the changes in Q and in the resonance frequency are reflected by a change in phase between the voltage and current waveforms of the driving signal. If the phase difference is detected, the analog output of the detector can be used as an indication of the acoustic impedance of the medium surrounding the transducer element. If the sound speed in the medium is known, then the analog output can be interpreted in terms of bulk density of the medium. Such an instrument would then be well suited for in situ determinations of bulk density in conjunction with in situ determination of compressional wave sound speed.

During the current contract year, work in this area has been concerned with building and testing a laboratory prototype of an instrument to measure acoustic impedance. Figure 15 shows a block diagram of the electronic system used to make measurements. The variable oscillator, pulse gating circuit, and 3 W power amplifier are all laboratory type units and are used to generate an electrical sine wave pulse to drive the transducer element. Pulse techniques are necessary in order to eliminate interference from the boundaries of the laboratory media. The comparators are used to convert the waveforms of the voltage and current pulses into square wave pulses to eliminate any interference from amplitude changes in the signals. The two outputs of the comparators are phase detected by a multiplier circuit whose output is the product of the two input voltages. This

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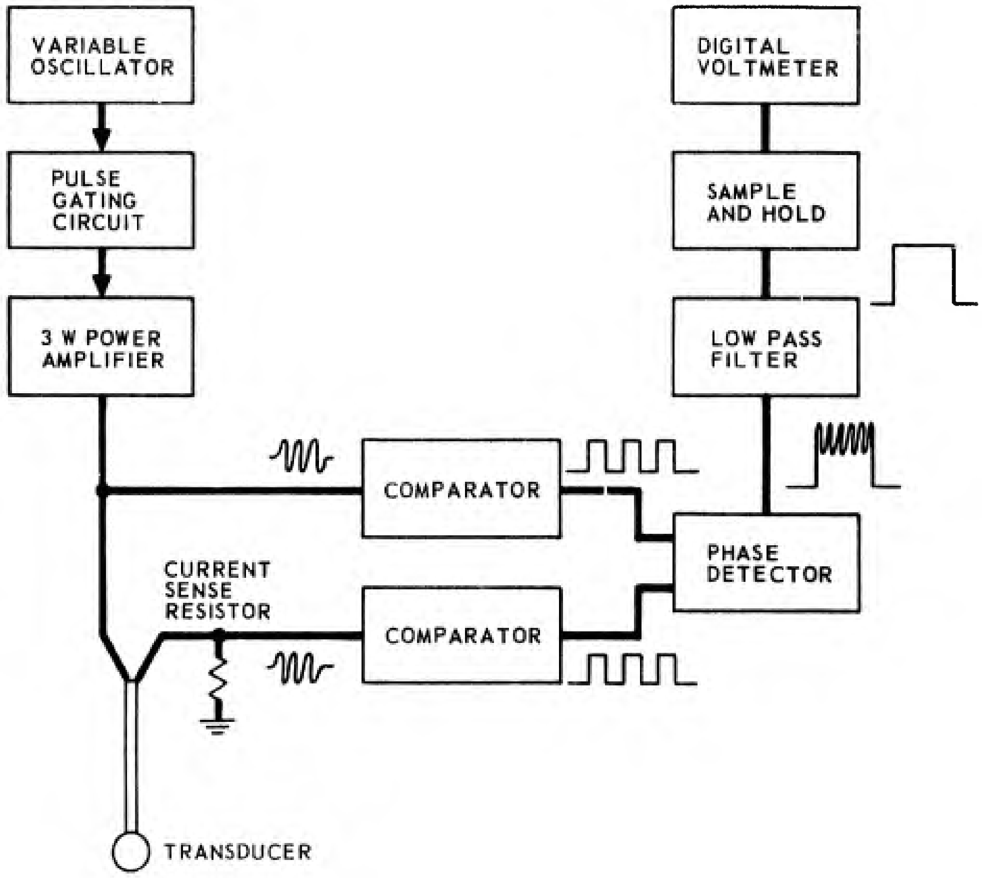

FIGURE 15
BLOCK DIAGRAM OF ACOUSTIC IMPEDANCE MEASURING ELECTRONICS

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output is a sine pulse at a frequency twice that of the incoming pulses with a zero mean value if the phase difference between the incoming pulses is zero. For phase differences either positive or negative, the mean value of the output pulse is also positive or negative. Passing this output through the low pass filter produces a square pulse whose height is thus dependent upon the phase difference of the input signals. This pulse height is sampled by a sample-and-hold circuit to produce an analog voltage which varies with the phase of the voltage and current waveforms of the transducer element.

As yet the only transducer that has been used to make measurements has been a 0.5 in. o.d. spherical ceramic element mounted on a slender rod to facilitate penetration of a sediment. The element was encapsulated in a thin sheath of polyurethane potting compound to prevent contamination of the ceramic by water. Measurements were made by placing the transducer element in various media and reading the output of the sample-and-hold circuit with a digital voltmeter. Figure 16 shows a plot of the output of the phase detecting circuitry versus acoustic impedance determined by measuring the bulk density and the compressional wave sound speed of the media. Four different frequencies were used in the determination to check frequency dependence.

It is evident from Fig. 16 that at some frequencies the relation between phase and acoustic impedance is very nonlinear. The readings taken at 175 kHz show a fairly linear portion from about 1.5×10^5 g/cm^2/sec on up. Much more data must be taken before the behavior of this system can be fully understood. Investigation is also proceeding into the nature of the relationship between the output of the system and the temperature of the transducer and medium.

It was found necessary to have the comparators and phase detector mounted as close to the transducer element as possible since the phase shift due to cable capacitance would otherwise swamp the effect from acoustic impedance changes. For this reason the electronic

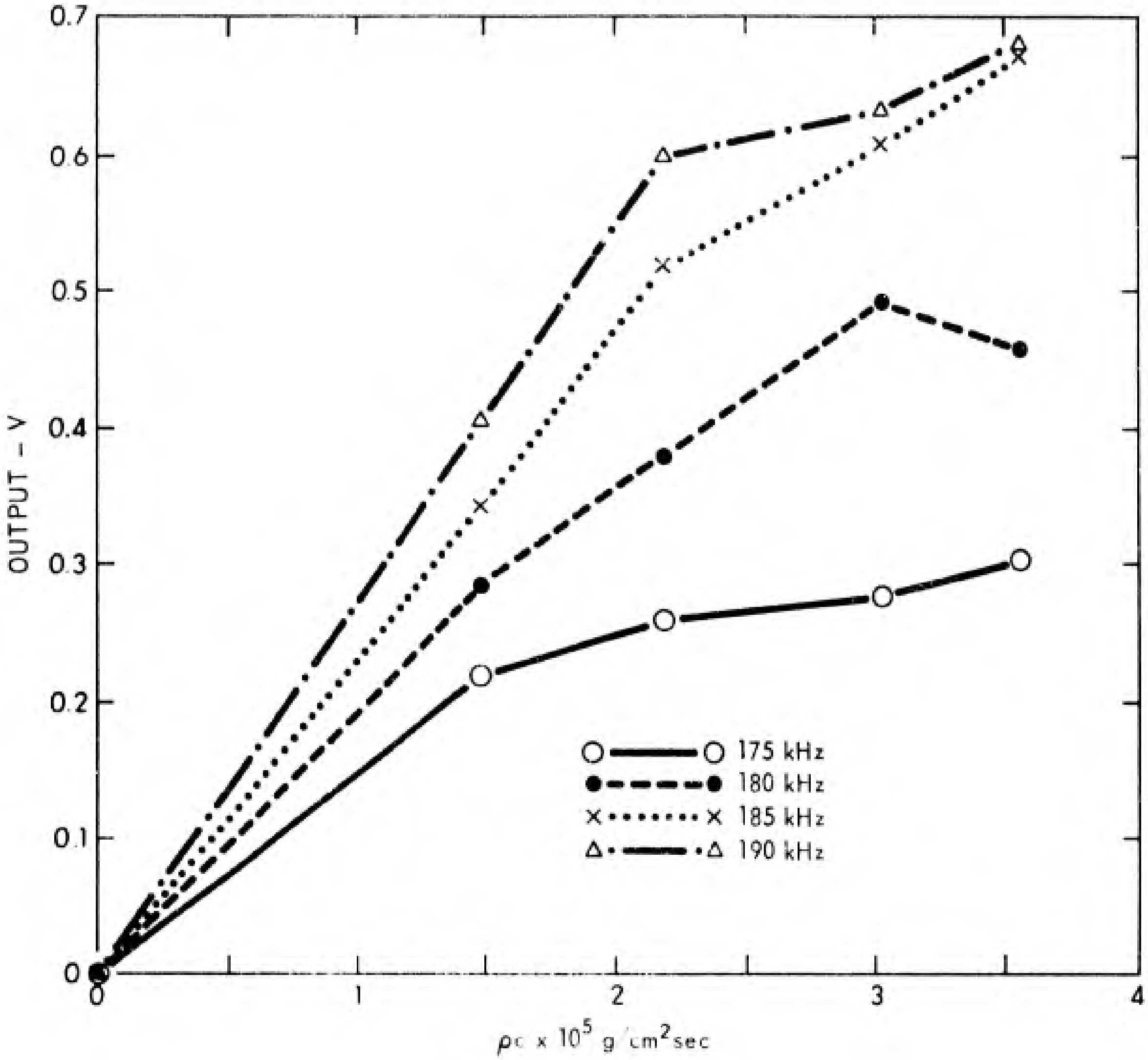

FIGURE 16
RELATIONSHIP BETWEEN ACOUSTIC IMPEDANCE AND PHASE DETECTOR OUTPUT

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phase detecting circuit is mounted at the top of the rod and potted in polyurethane with a cable connecting it to the filter and sample-and-hold circuit.

VI. SEDIMENT ENGINEERING PROPERTIES

Due to the growing interest in engineering in the ocean environment, a knowledge of the static mechanical parameters of bottom sediments has become of primary importance. Most of these parameters are difficult to determine in situ, especially in deep water, and determinations upon samples quite often do not reflect true values due to disturbance of the sample upon removal. There are indications that correlations exist between many of the static engineering properties of a sediment and its various acoustic properties. It is the purpose of this task of the contract to investigate correlations between acoustic and engineering properties in conjunction with the acoustic investigations of the other contract tasks.

Most of the work done so far has been to investigate and establish the particular parameters for initial investigation. The static mechanical properties that have been chosen include the following.

1. Mean grain size
2. Percent water
3. Porosity
4. Bulk density
5. Atterberg limits
   A. Liquid limit
   B. Plastic limit
6. Vane shear strength for cohesive sediments
7. Core penetrometer shear strength for noncohesive sediments

The first four parameters listed require only normal laboratory equipment for determination and have been routinely measured for the sediments that have so far been used for acoustic work. The last three parameters require specialized equipment for measurement. Of

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these, the apparatus for determination of the Atterberg liquid limit has been constructed but not yet calibrated for use. Figure 17 shows a photograph of the finished instrument, which consists of a 54 mm i.d. x 58 mm o.d. hemispherical brass cup which is raised and allowed to drop by a cam arrangement attached to a hand crank. A determination is made by placing wet sediment in the cup, cutting a standard size groove with the special grooving tool shown, then using the hand crank to tap the cup against the base at a 2 Hz rate. The number of taps required to close the groove for 1/2 in. is determined. Percent water is thus determined for subsamples of the sediment when the number of taps is within the range of 15 to 35 blows. Within this range, there is a linear relation between the logarithm of the number of blows and percent water so that water content can be determined for the standard number of 25 blows. This water content expressed as percent is the Atterberg liquid limit.

The Atterberg plastic limit requires no equipment for determination. A small sample of the wet sediment is rolled between opened palm and a flat surface such that a thin thread of the material is formed. The water content is determined as the point at which a 1/8 in. thick thread breaks up into 1/8 to 1/2 in. parts. This water content expressed as percent is the Atterberg plastic limit.

Figure 18 shows a schematic representation of the vane shear apparatus under construction. The vane blades (2 cm diam x 2 cm long) are connected to a long thin (20 cm long x 0.32 cm diam) shaft which in turn is fastened to a metal plate. Strain gauges are bonded on each side of each arm of the plate to form a bridge to measure the torque exerted on the vane shaft. The outside edges of the strain gauge plate are connected to a shaft rotated by a 1/60 rpm electric motor. A potentiometer is fastened to the motor shaft to provide an electrical analog of the shaft position. Thus the vane blades are rotated at a rate of 6° per minute and the torque exerted on the vane blades by the shear resistance of the sediment is measured by the strain gauge bridge.

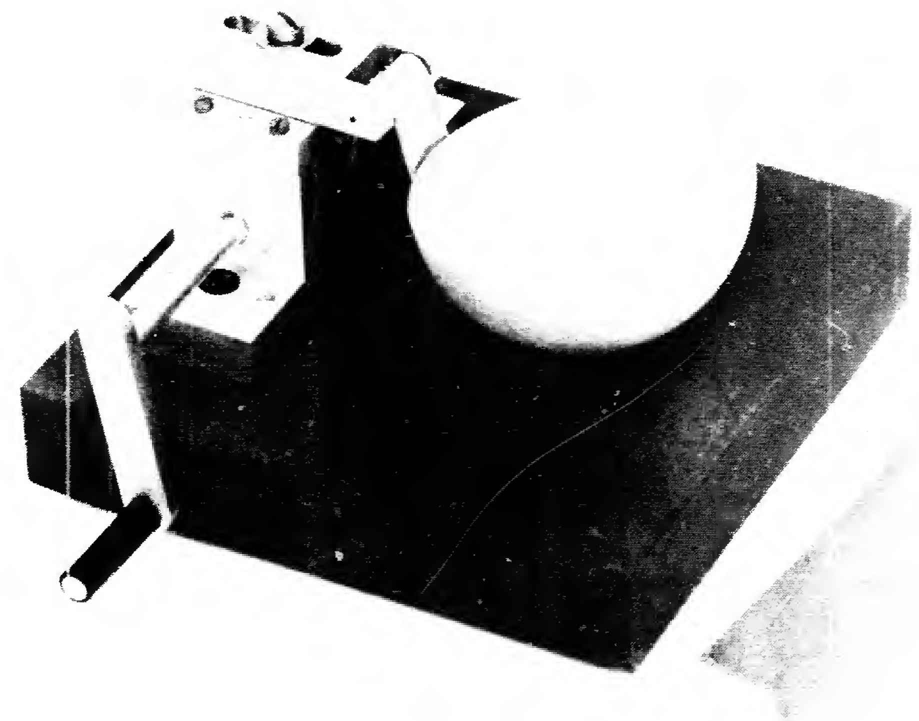

FIGURE 17
DEVICE TO MEASURE THE ATTERBERG LIQUID LIMIT

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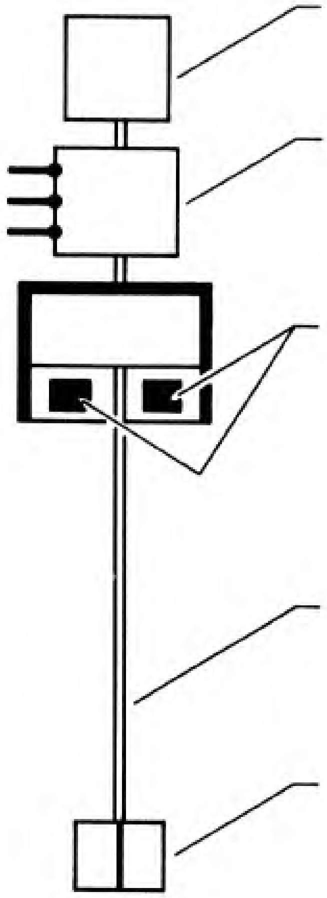

FIGURE 18
SCHEMATIC REPRESENTATION
OF VANE SHEAR APPARATUS

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This torque is plotted versus shaft rotation on an x-y plotter to determine the vane shear strength of the sediment.

The cone penetrometer is similar in operation to the vane shear apparatus except, instead of a vane being rotated with its torque measured, a shaft with cone attached is pushed into the sediment at a constant rate of speed and the force on the shaft is measured. Figure 19 shows a schematic representation of this apparatus. The cone and shaft are forced downward into a sediment by a rack and pinion gear arrangement attached to an electric motor. Force on the cone is measured by a strain gauge bridge bonded to a metal crossarm attached at the center to the shaft and at the ends to the rack and pinion. Vertical position of the shaft is recorded by a potentiometer attached to the motor shaft. Force is plotted versus cone presentation to determine shear strength.

Neither the vane shear nor cone penetrometer devices has been constructed. Parts are being made for the vane shear device and the cone penetrometer is in the design stage.

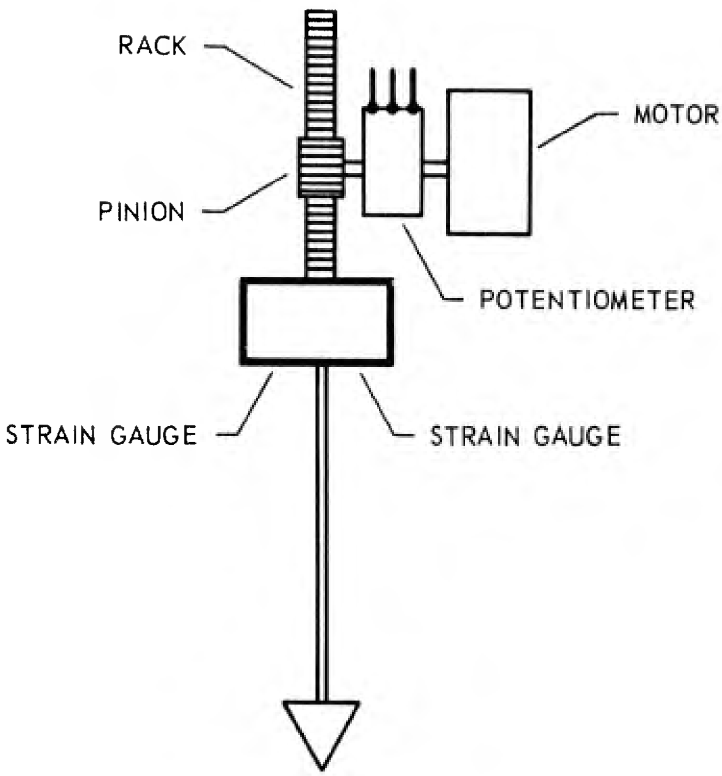

FIGURE 19
SCHEMATIC REPRESENTATION OF
CONE PENETROMETER APPARATUS

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VII. CONCLUSION

The following statements summarize what has been presented.

1. Five different transducer types have been constructed and evaluated for shear wave measurements. The latest type shows the most promise, being capable of making measurements on sediment with shear moduli in the range of natural ocean bottom clays and sands.

2. Linear relationships have been shown to exist between the phases of the driving waveforms of a ceramic transducer and the acoustic impedance of a sediment into which it is imbedded.

3. Various engineering parameters of sediments for correlation to acoustic parameters have been identified. Instruments to measure these engineering parameters in the laboratory are being built.

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