COMPRESSIONAL WAVE SPEED AND ABSORPTION MEASUREMENTS IN A SATURATED KAOLINITE-WATER ARTIFICIAL SEDIMENT

Charles Allen Martinek

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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by

Charles Allen Martinek

Thesis Advisor: R. S. Andrews
Co-Advisor: O. B. Wilson, Jr.

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Charles Allen Martinek
Lieutenant, United States Navy
B.S., United States Naval Academy, 1966

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ABSTRACT

The absorption coefficient for compressional waves in a water-saturated kaolinite clay was measured in the frequency range 100 to 150 kHz using a pulse technique with spherically diverging waves. The measurement also permitted determination of the sound speed, V_p. For one condition of the clay with a 77% porosity, the sound speed was 1422 m/sec. The absorption coefficient, a, was found to be frequency dependent, satisfying the empirical relationship a = 0.033 f dB/m, f being the frequency in kHz. No dispersion of wave speed with frequency was observed. These results were used together with the results of dynamic shear (rigidity) modulus measurements made with a torsional wave viscoelastometer to calculate the complex Lamé constants of a viscoelastic model.

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I. INTRODUCTION

For some problems of sound propagation in the ocean, the ocean bottom can be satisfactorily described using the Rayleigh model. Mackenzie [1] showed that the Rayleigh model can be applied to cases where sound was obliquely reflected at grazing angles (measured between the ray and the plane of the bottom) greater than the critical angle. However, at smaller grazing angles the model can not account adequately for bottom losses. In those cases where the attenuation of sound in the sediment becomes important, a more realistic viscoelastic model should be employed which considers the effects of rigidity and absorption.

The complex Lamé constants (λ, μ, λ' and μ') of the viscoelastic model are theoretically related to four observable quantities, the speeds of propagation of compressional and shear waves and the attenuation of these waves. The effectiveness of the viscoelastic model is therefore governed by the precision and accuracy of the values obtained for the complex viscoelastic moduli. The moduli can be calculated through measurements of the acoustic properties mentioned above. Measurement of shear wave propagation by direct methods is the most difficult of the observations to make, particularly in soft sediments, because of its high attenuation and the physical problem of generating transverse wave motion. One procedure to obtain indirectly the shear wave speed is the measurement of the speed of a surface wave (Stoneley wave or Rayleigh wave) propagating along the sediment-water interface. When the speed and attenuation of the Stoneley wave is determined, shear wave speed and attenuation constants of the sediment can be determined [2]. Other prerequisites for this type

of calculation require the knowledge of compressional wave speed and attenuation and the density of the sediment. Hamilton et al. [3] provide a sample calculation illustrating this procedure.

Numerous researchers have conducted tests to determine the compressional wave speed and attenuation and, to a lesser extent, surface wave speed and attenuation of sediments either in situ or in the laboratory. Urick [4, 5] developed expressions for compressional wave speed and absorption in kaolinite suspensions. Urick and Ament [6] also outlined a theory for a complex propagation constant whose real part yielded a wave speed and whose imaginary part yielded an absorption coefficient.

Laughton [7] conducted laboratory experiments on ocean sediments, measuring compressional and shear wave speeds only. He was able to make direct shear measurements on compacted sediments, but not on uncompacted material because of its low rigidity.

Hampton [8] reported on the results of measurements on the acoustic properties of sediments, including compressional wave speed and attenuation measurements of dispersed and undispersed kaolinite sediments.

Hamilton and his associates at the Naval Undersea Research and Development Center have conducted both Stoneley and compressional wave measurements. Their efforts culminated with in situ measurements of both waves from the research submersible DEEPSTAR 4000 at stations close together and in the same sedimentary environment. With the data, Hamilton was able to calculate both elastic and viscoelastic constants for the sediments. They were prevented from making both sets of measurements during the same dive by the quantity of unique equipment required for each measurement procedure.

This problem may be reduced by use of a torsional wave visco-elastometer developed at the Naval Postgraduate School by Hutchins [9], Cohen [10] and Bieda [11]. The instrument measures the loading effects caused by the rigidity of a sediment on a torsionally vibrating rod. These effects can be analyzed to calculate the real and imaginary parts of the shear (rigidity) modulus. Determination of the shear modulus by this method could possibly provide a better method to determine shear wave properties than by conducting Stoneley wave speed and attenuation measurements.

This experiment was part of a process for validation of the visco-elastometer measurement method. Since the viscoelastic parameters also relate to the sound absorption, it is necessary to carefully measure the sound speed and absorption in sediment. Comparison of the results of these measurements with those obtained by the viscoelastometer can give an indication of the validity of the latter method.

A compressional sound wave was propagated by an electrostatic source through a water-saturated kaolinite sediment. The signal received by a hydrophone was recorded and analyzed to obtain values of the compressional wave speed and absorption. Viscoelastometer measurements were then made on a core sample of the sediment in which the sound wave experiment was conducted.

II. THEORY

A. COMPRESSIONAL WAVES

For spherically diverging waves, the equation for the sound pressure level (SPL) in decibels can be written [12]:

$$SPL = SL - 20 \log_{10} r - ar \qquad (1)$$

where SL is the source level, r is the range and a is the absorption coefficient. The logarithmic term represents the spherical spreading loss in decibels. By rearranging terms, the relation

$$SPL + 20 \log_{10} r = SL - ar \qquad (1A)$$

provides an equation which is convenient for plotting experimental data on linear graph paper. The slope of the curve of Equation (1A) should be a straight line with units of decibels/unit length, the absorption coefficient. The intercept of this curve at a unit distance is the value of the source level in decibels. Equation (1) assumes a homogeneous and isotropic medium and the absence of reflecting surfaces. For a finite sized source, the inverse square law divergence applies only at distances from the source that are large in comparison with the radius of the piston source. Due to interference effects, the axial pressure near the surface of a piston undergoes wide variations with changes in range, until the distance is greater than $d^2/2\lambda$, where d is the diameter of the piston and λ is the wavelength [13].

B. THE VISCOELASTIC MODEL

Following the development used by Hamilton et al. [3], the viscoelastic model uses complex Lamé constants $(\mu + i\mu')$ and $(\lambda + i\lambda')$ to account for absorption. For simple harmonic motion, the time factor $e^{i\omega t}$ is used. Compressional and vertically polarized shear waves traveling in the sediment can be described in terms of displacement potentials ϕ and ψ. For a viscoelastic solid, these displacement potentials must satisfy the following wave equations:

$$\rho \frac{\partial^2}{\partial t^2} \phi = (\lambda + 2\mu)\nabla^2\phi + (\lambda' + 2\mu') \frac{\partial}{\partial t} \nabla^2\phi \tag{2}$$

$$\rho \frac{\partial^2}{\partial t^2} \psi = \mu\nabla^2\psi + \mu' \frac{\partial}{\partial t} \nabla^2\psi \tag{3}$$

where ρ is the density of the solid. Bucker [14] has solved these equations in order to determine the complex Lamé constants. The resulting equations are:

$$1/V_p^2 - 1/t_p^2 = \rho/(\lambda + 2\mu)(1 + q_p^2) \tag{4}$$

$$2/V_p t_p = \rho q_p/(1 + q_p^2)(\lambda + 2\mu) \tag{5}$$

$$1/V_s^2 - 1/t_s^2 = \rho/\mu(1 + q_s^2) \tag{6}$$

$$2/V_s t_s = \rho q_s/\mu(1 + q_s^2) \tag{7}$$

where V_p and V_s are, respectively, the compressional and shear wave speeds and

$$q_p = \frac{\lambda' + 2\mu'}{\lambda + 2\mu} \tag{8}$$

$$q_s = \frac{\mu'}{\mu} \quad .$$

Here, t_p and t_s are related to the absorption of the compressional and shear waves by:

$$a_p = -20(\log_{10} e)(\omega/t_p) \tag{9}$$

$$a_s = -20(\log_{10} e)(\omega/t_s) \quad .$$

In this experiment, μ and μ' were determined from measurements by the viscoelastometer, and the compressional wave speed and absorption were determined by direct measurement. By using the viscoelastic equations, λ and λ' can be calculated. Values for the expected shear wave speed and absorption can also be calculated.

Assumptions and approximations upon which the model is based are listed below:

1. the use of complex Lamé constants to account for attenuation does not specify the mechanisms involved;

2. the dilatational or bulk viscosity is set equal to zero, i.e., $\lambda' + 2\mu'/3 = 0$;

3. the complex Lamé constants are independent of frequency, implying that the real parts, λ and μ, governing the compressional and shear wave speeds, and the imaginary parts, λ' and μ', governing energy losses are also independent of frequency (most observers, with the notable exception of Hampton [8], have not observed any dispersion with frequency);

4. absorption in decibels/unit length is assumed to increase linearly with frequency, $a = kf$ (Cole [15] and Wood and Weston [16] have found an approximate linear dependence in natural sediments).

C. THE VISCOELASTOMETER

The description, theory, and operation of the viscoelastometer have been thoroughly reported by Lasswell [17], Bieda [11], Walsh [18] and others. The viscoelastometer, as shown in Fig. 1, consists of a rod-shaped torsional mechanical oscillator which is excited at one of its mechanical resonance modes by a torsional piezo-electric crystal located at its center, setting up a standing wave along the axis of the system. The torsional motion of the rod surface in contact with another medium generates a shear wave which propagates radially outward from the rod. The loading effects of the medium, such as a soft clay, cause a measureable change in the mechanical damping and resonance frequency of the viscoelastometer. Electrical measurements of these changes can be related to the complex rigidity modulus through a procedure which uses Newtonian fluids for calibration of the device.

III. EQUIPMENT AND PROCEDURES

A. THE SEDIMENT TANK

An artificial ocean sediment was formed by a saturated kaolinite-water mixture contained in 4 ft by 8 ft by 3 ft steel tank (Fig. 2). The tank rests on 9 inches of sand and is surrounded by 1 ft of sand on the lower half of the tank's sidewalls. The sand was installed to act as a damping mechanism for reflection of waves from the walls of the tank and floor vibrations. Kaolinite clay is a hydrated aluminum disilicate with a grain diameter comparable to the clay size particles found in many ocean bottom sediments. It was chosen for this experiment for the additional reason that it is commercially available in a fairly pure state. The depth of the clay was approximately 70 cm.

The bottom of the tank is lined with $\frac{1}{2}$-inch diameter copper tubing which can be used for heating the clay with steam. Prior to conducting measurements, the clay was covered with water, thoroughly stirred in an attempt to break up any clumps and to homogenize it, and heated to drive off any gas bubbles that may have existed in the clay. Hampton [8] emphasized the importance that even small quantities of gas can have on acoustic properties.

B. COMPRESSIONAL WAVE MEASUREMENTS

A horizontally-oriented beam of compressional waves was generated in the clay approximately 25 to 30 cm below the clay-water interface by a 7.1-cm diameter electrostatic transducer similar to one constructed and described by Palatini [19]. The transducer was a piston-type source with a 1-mil thick aluminum coated Mylar film (a DuPont polyester film)

attached to a slightly roughened flat plate. The transducer was polarized by a 300-v battery. Since a thin layer of air was entrapped between the plate and the Mylar film, the air pockets acted as a spring against which the film moved when the applied alternating signal voltage gave rise to an alternating electrostatic force. The motion was expected to be essentially uniform over the surface and the response was shown by Palatini to be independent of frequency at high frequencies in the mass-controlled region where $kd \gg 1$ (d is the diameter, k is the propagation constant).

The electrical drive to the transducer consisted of a gated sine wave, usually eight cycles, which was provided by an oscillator and a tone-burst generator. The output from the tone-burst generator was passed through an additional gate and clipping circuit developed by Cohen [10] to reduce leak-through when the gate is closed. The driving tone-burst was amplified in a power amplifier and stepped up with a 6:1 transformer, passed through a polarizing circuit driven by a 300-v battery and then to the electrostatic transducer. The frequency of the signal was controlled at the oscillator and monitored on a frequency counter. The voltage output could be controlled at both the oscillator and the power amplifier and was kept constant at 53.5 v RMS by monitoring it on a vacuum tube voltmeter.

The receiver was a $\frac{1}{2}$-inch by $\frac{1}{2}$-inch cylindrical barium titanate hydrophone mounted on a rack-and-pinion assembly to provide smooth and easy positioning of the transducer. The received signal was amplified (usually 60 dB) and passed through 60- and 120-Hz filters to eliminate low frequency hum. High frequency noise was reduced by also passing the signal through a low pass/high pass filter set at 180 and 85 kHz. The signal was fed into the boxcar

integrator where it was scanned by a slowly moving gate and reproduced on an X-Y recorder. Both the gate and the received signal were monitored on the oscilloscope. A typical record of the direct arrival sound pulse is shown in Fig. 3. A block diagram of the system is shown in Fig. 4. This signal processing method had the advantage that it provided records which have enhanced signal to noise ratios and which can be measured more precisely than can photographs of the cathode ray oscilloscope.

The boxcar integrator synchronously sampled an input signal with a variable width, variable delay gate, which can be slowly scanned across the input signal. That signal passed by the gate was averaged by variable time constant integrators, the output of which was the average of the number of repetitions of the input signal over the gate width interval. Because the average value of noise over a number of repetitions was zero, an improvement in signal to noise ratio occurred. When the gate was scanned across the return signal from the transducer, the waveform was reproduced on the X-Y recorder.

The signals were analyzed to obtain both compressional wave speed and absorption. The gate on the boxcar integrator was calibrated with a time-mark generator at 10-μsec intervals from 0% to 100% of the boxcar's scan/delay scales. The fixed delay (16 μsec) between the trigger of the transducer signal and the 0% value on the scan/delay scales was determined. The time of the first arrival of the signal was then read off the waveform trace and the delay time was added to get the total travel time. This was divided into the horizontal range to determine the compressional wave speed.

The absorption coefficient was determined by a comparison of the amplitudes measured in millivolts at various ranges. During the course of the experiment, it became clear that, in addition to the direct path signal, there was some interference caused by possible side wall reflections, sediment-water interface reflections and other undetermined multipath transmissions. For this reason, only the first two and one-quarter cycles were used for analysis since they appeared to be free of any such interference. The amplitudes in millivolts of the first three positive peaks and the first two negative peaks were measured. Then the values for four half-cycles were determined by adding the amplitudes of the first positive and first negative peaks, the first negative and second positive peaks, and so forth. The values obtained for the four segments were then averaged, and the average was used as a representative amplitude for the given frequency and range. The level of this voltage was calculated in decibels relative to an arbitrary value of 1 mv by the equation:

$$SPL = 20 \log_{10} (\text{voltage, mv})$$

The reference distance for the spherically divergent term was chosen as 1 cm also for the reason of convenience. Equation (1A) was entered with the SPL values out to a range of 1 m and plotted as illustrated in Fig. 5. The slope theoretically should be a straight line, the value of which is the absorption coefficient in decibels/meter. Since scatter did exist, the slope was determined by a least squares fit. A linear regression program was run on a Hewlett-Packard 9100A calculator to determine the best fit by minimizing the sum of the squares of the deviations of the data points from the straight line.

C. THE VISCOELASTOMETER

The viscoelastometer used to provide shear modulus data was the same type of instrument used by Bieda [11] and Lasswell [17]. It is 10.5 inches long with a $\frac{1}{2}$-inch diameter cylindrical rod whose torsional oscillation was controlled by a hollow barium titanate transducer mounted in the center of the rod. The transducer was 1.5 inches long and $\frac{1}{2}$-inch in diameter. It was constructed from an axially-polarized cylinder which was cut into two parts along the longitudinal axis and rejoined after the inversion of one half and the insertion of two electrode grids. The transducer was wrapped in fiberglass thread under tension and covered with an epoxy resin to improve the contact at the joints. The rod was constructed from two sections of a constant modulus alloy, NI-Span-C. These parts were heat treated and highly polished.

The viscoelastometer was supported by clamping at the center of the transducer using a tubular steel framework which housed the electrical leads to the transducer. In this way the clamp did not interfere with the functioning of the viscoelastometer since the transducer center was a node of torsional motion for all the resonant modes. The electrical connections were kept watertight by the application of a silicone rubber coating.

The rod was first calibrated in Newtonian fluids of known viscosity. The resonant frequency and electrical resistance were then measured in air and in the artificial sediment in order to obtain the changes in resonant frequency and electrical resistance required to calculate the rigidity. A sample core of the sediment in which the sound wave experiment was conducted was obtained and placed in a water bath maintained at

a temperature of 20 C. Three sets of measurements were taken on the core approximately 12 hr apart which were used by Lieutenant J. Morgan to calculate the real and imaginary parts of the rigidity.

D. WET DENSITY AND POROSITY

The wet density is the weight per unit volume of the water-saturated sediment. A known volume of the sediment was obtained by the use of an instrument fabricated by the Physics Shop at the Naval Postgraduate School and shown in Fig. 6. This sediment sampler had a known volume of 24.68 cm^3. The sampler could be lowered to the desired depth in the sediment with the only disturbance to the sediment being along the walls of the cylinder. When in place, top and bottom plates were rotated across the cylinder, trapping the sediment enclosed. The bottom plate contained a rubber gasket to prevent leakage of water while the sampler was in the upright position. The sample was emptied into a weighing dish and weighed. The ratio of the wet weight divided by the volume equaled the wet density. After being heated in an oven at 105 C for 24 hr, the sample was weighed again, with the weight loss assumed to be entirely due to evaporation of the entrapped water. Assuming that 1 g of water occupies 1 cm^3, the difference in weight in grams between the wet and dry sample was equal to the volume of voids in cubic centimeters in the sample. Porosity was then determined by the relationship:

$$\text{Porosity} = \frac{\text{Volume of Voids}}{\text{Total Volume}} .$$

Hampton [8] used the term volume concentration which is related to porosity by:

$$\text{Volume Concentration} = 1 - \text{Porosity}.$$

IV. RESULTS AND DISCUSSION

Table I shows the results obtained from the compressional wave speed measurements in the tank. The speed of sound in water was computed using Wilson's formula [12]. The horizontal range measurements were accurate to within 0.2 cm; the determination of arrival time was accurate to within 5 μsec. The calculations of the compressional wave speed were then accurate to within ±1.5%. The ratio of the sound speed in the sediment to that in water is somewhat lower than would be expected. Cohen [10] and Walsh [18] both observed ratios greater than 0.98 for kaolinite-water sediments with approximately the same porosity. Data collected by Hamilton [20] for shallow water sediments off San Diego gave a sound speed ratio of 0.97 or greater.

A possible explanation for this difference was the existence of some gas bubbles in the sediment. Another indication of this possibility was the observation of some acoustic reverberation in the received sound pulse following the direct arrival. Since the reverberation was much smaller than the direct arrival, the scattering cross-section per unit volume of the inhomogeneities which caused the reverberation must also have been small.

The absorption coefficient was determined using Equation (1A) and is shown in Table I for the frequencies used in the experiment. Fitting these points with a linear equation in frequency resulted in an absorption coefficient

$$a = kf \quad \text{dB/m}$$

with $k = 3.3 \times 10^{-2}$, and where f is the frequency in kHz. This result agrees well with studies made by Hamilton [21]. He predicted a value for k of between 0.02 and 0.06 for an artificial sediment with porosity in the 70 to 80% range. Hampton [8] reported a value for the absorption of approximately 4 dB/ft (approximately 13 dB/m) for kaolinite of nearly the same porosity at 100 kHz with a frequency dependence of $f^{1.37}$. Wood and Weston [16] determined an absorption coefficient equal to 2×10^{-2} dB/ft-kHz (approximately 6.6 dB/m at 100 kHz) in mud that showed a linear frequency dependence.

One of the original objectives of this research was to determine both the compressional and shear wave speeds and absorption in the sediment. Attempts to duplicate Walsh's [18] measurements of surface waves were in vain. Although basically the same equipment and procedures were used, a surface wave could not be observed in this sediment. Since a direct comparison of the results obtained from applying the viscoelastic equations to those obtained from the viscoelastometer could not now be made, it was decided to assume a value for the shear wave speed in order to make a rough comparison of the two methods.

Values for the real and imaginary parts of the shear modulus (μ and μ') as computed from viscoelastometer measurements are listed in Table II for one of its mechanical resonance modes. The values are the same order of magnitude as those obtained by Cohen [10] in kaolinite. Although Walsh [18] had arrived at a value for the shear wave speed (V_s) of approximately 23 m/sec, both Cohen's values and the measurements reported here indicate that a shear wave speed of less than 5 m/sec is more realistic for the very soft sediment being studied. Values for μ and μ' were calculated using the following viscoelastic equations [3] and experimental data:

$$\mu = \rho V_s^2$$

$$t_p = \frac{8.686\omega}{a}$$

$$q_p = \frac{2}{(t_p/V_p - V_p/t_p)}$$

$$\lambda + 2\mu = \frac{V_p t_p q_p}{2(1 + q_p^2)}$$

$$\mu' = \frac{3q_p(\lambda + 2\mu)}{4}$$

$$\rho = 1.386 \text{ g/cm}^3$$

$V_s = 5 \times 10^2$ cm/sec (assumed value)

$\omega = 2\pi(1.56 \times 10^4$ Hz) where 15.6 kHz was one of the resonant modes of the viscoelastometer.

$a = 5.15 \times 10^{-3}$ dB/cm (extrapolated from 100 kHz to 15.6 kHz)

$V_p = 1.422 \times 10^5$ cm/sec.

Table II compares the results of the two methods. The value of μ was equal to 3.5×10^5 dyne/cm^2 from theory, the same order of magnitude as that measured by the viscoelastometer. The calculated value of μ' was 360×10^5 dyne/cm^2, two orders of magnitude greater than the viscoelastometer measurement. Examination of the parameters in the viscoelastic equations reveals that the determination of μ' is relatively insensitive

to changes in the absorption coefficient or the shear wave speed when V_s is small. It should be noted that the viscoelastometer results used here are approximate since they are based on a very limited number of observations. However, they are comparable to observations reported by Cohen [10] for a very porous kaolinite mixture.

V. EXPERIMENTAL PROBLEMS

The sediment, even after being thoroughly stirred, lost its homogeneous state in a matter of hours. Settling and compaction took place which produced distinct vertical gradients. By lowering one's arm through the clay, a definite change in the sediment rigidity could be felt, ranging from a nearly fluid slurry at the surface to a compacted mass at the bottom. The stratification caused by the changes in density and porosity with depth was neither spatially nor temporally uniform. Horizontal gradients, while not as pronounced as the vertical gradients, also were present. The presence of small clumps of clay caused further discontinuities in the gradients. Pronounced and changing stratification and gradients then did not allow an ideal medium for the propagation of sound waves and comprised a major problem area.

After the sediment had been reasonably outgassed and homogenized, initial attempts to obtain compressional wave measurements were thwarted by equipment problems. Among those were the shorting out of the transducer by water leaking into it and low signal-to-noise ratios caused by high frequency noise probably generated internally by some of the equipment. By the time these and numerous minor procedural and equipment problems were corrected, the sediment had time to develop stratification and gradients. Attempts to determine sound absorption coefficients showed that the medium no longer exhibited the inverse square law for spherical spreading and was therefore unsatisfactory for further experiments.

The sediment was again heated and thoroughly stirred. With increased porosity and decreased density, the sound speed decreased as expected [22], but once again the value was low judging by the ratio of the sediment to water sound speeds. Some reverberation due to scattering from bubbles or other inhomogeneities was observed. This could have affected the observed absorption coefficient, but the effect is believed to have been small.

Failure to obtain a surface wave measurement indicated other problem areas. The sediment in this report was the same kaolinite used by Walsh [18]. However, these measurements were made with a layer of water overlying it while, in Walsh's experiments, the sediment was covered with a thin film of water and the surficial layers were much stiffer. With the combined effects of the water layer and the extensive stirring of the sediment shortly before the experiment, the sediment surface was extremely soft. Attempts to place geophones on the sediment surface resulted in the geophones sinking several centimeters or more below the water-sediment interface. Both the soft nature of the sediment surface and the weight of the geophones were contributing factors. Attempts to keep the geophones on the surface by placing them on a thin plastic sheet also failed. The sheet was pushed beneath the surface when the geophones were placed on it. As a result, no surface waves could be observed.

VI. CONCLUSIONS AND RECOMMENDATIONS

An experimental method has been used to determine the speed of propagation and absorption of compressional waves in a saturated kaolinite-water mixture. For one case of the sediment having a porosity of approximately 77%, a wet density of 1.386 g/cm^3 and a temperature of 20 C, the sound speed was determined to be 1422 m/sec and the absorption coefficient described by $a = 3.3 \times 10^{-2} f$ dB/m where f is the frequency in kHz. Data taken by the viscoelastometer on a core of the same sediment confirmed earlier results reported by Cohen [10] for basically the same kaolinite-water mixture. In addition, Bieda [11] and Lasswell [17] took visco-elastometer measurements in natural marine sediments with good correlation between their results. Therefore, these results seem to indicate that the viscoelastometer yields reasonable quantitative estimates of the shear moduli. Calculation of μ from the observed physical properties (V_s was assumed since it could not be determined) also confirms that the visco-elastometer measurements appear to be reasonably accurate. However, a large discrepancy existed when μ' was calculated since the viscoelastic equations produced a result which was two orders of magnitude greater than would be expected for this case. The value of μ' is strongly influenced by the $\lambda + 2\mu$ term. This in turn is influenced by the difference in V_s and V_p. In sediments with small shear wave speeds, V_s no longer is a significant percentage of V_p, and the calculated μ' becomes too large.

It is recommended that this discrepancy be resolved by further study. If the viscoelastometer is producing valid results, and previous data indicates that it is, then possibly the theory may be suspect for low values of shear wave speed. One assumption which may be questioned is that the

bulk viscosity is zero. If other factors are present which cause energy losses in sediments with small shear wave speed, the present theory may not totally account for them and thus may yield the anomalously high value for μ'. An example of computations by Hamilton [3] of viscoelastic constants for a sediment with a shear wave speed greater than 100 m/sec illustrated that reasonable results for μ' can be obtained from sediments that exhibit definite rigidity.

The data collected in this report for the sound speed and absorption were inadequate to provide a complete validation of the viscoelastometer method. It is necessary to obtain accurate values for both the compressional and shear wave speeds and the absorption. With those values, the complex Lamé constants for the viscoelastic model can be determined. When this experimental procedure can be satisfactorily accomplished, then results of viscoelastometer measurements on the same sediment can be compared to validate the effectiveness of the viscoelastometer method. If the viscoelastic theory is found to be invalid for small shear wave speeds, another sediment having more rigidity may have to be used in the tank, or else in situ measurements of natural sediments will have to be taken. If the theory is correct, then there is a serious question of the meaning of the imaginary part of the modulus determined by the viscoelastometer.

A recent doctoral dissertation by Borcherdt [23] offers a theoretical investigation of inhomogeneous body and surface plane waves in a generalized viscoelastic half space. Possibly the theoretical processes can be examined in this laboratory environment to provide more information on viscoelastic properties, in particular, the speed and absorption of shear waves.

TABLE I

COMPRESSIONAL WAVE AND SEDIMENT PROPERTIES

Frequency (kHz)	a (dB/m)	V_p (m/sec)	$V_{p\ sed}/V_{p\ wat}$	Temp (C)	Wet Density (g/cm^3)	Porosity (%)
100	3.3	1422				
125	4.2	1422	0.94	19.9	1.386	76.7
150	5.0	1422				

TABLE II

COMPARISON OF METHODS FOR DETERMINING SHEAR MODULI

Frequency	Theory		Viscoelastometer	
	μ	μ'	μ	μ'
(kHz)	(10^5 dyne/cm^2)		(10^5 dyne/cm^2)	
15.6	3.5	360	1.4	3.9

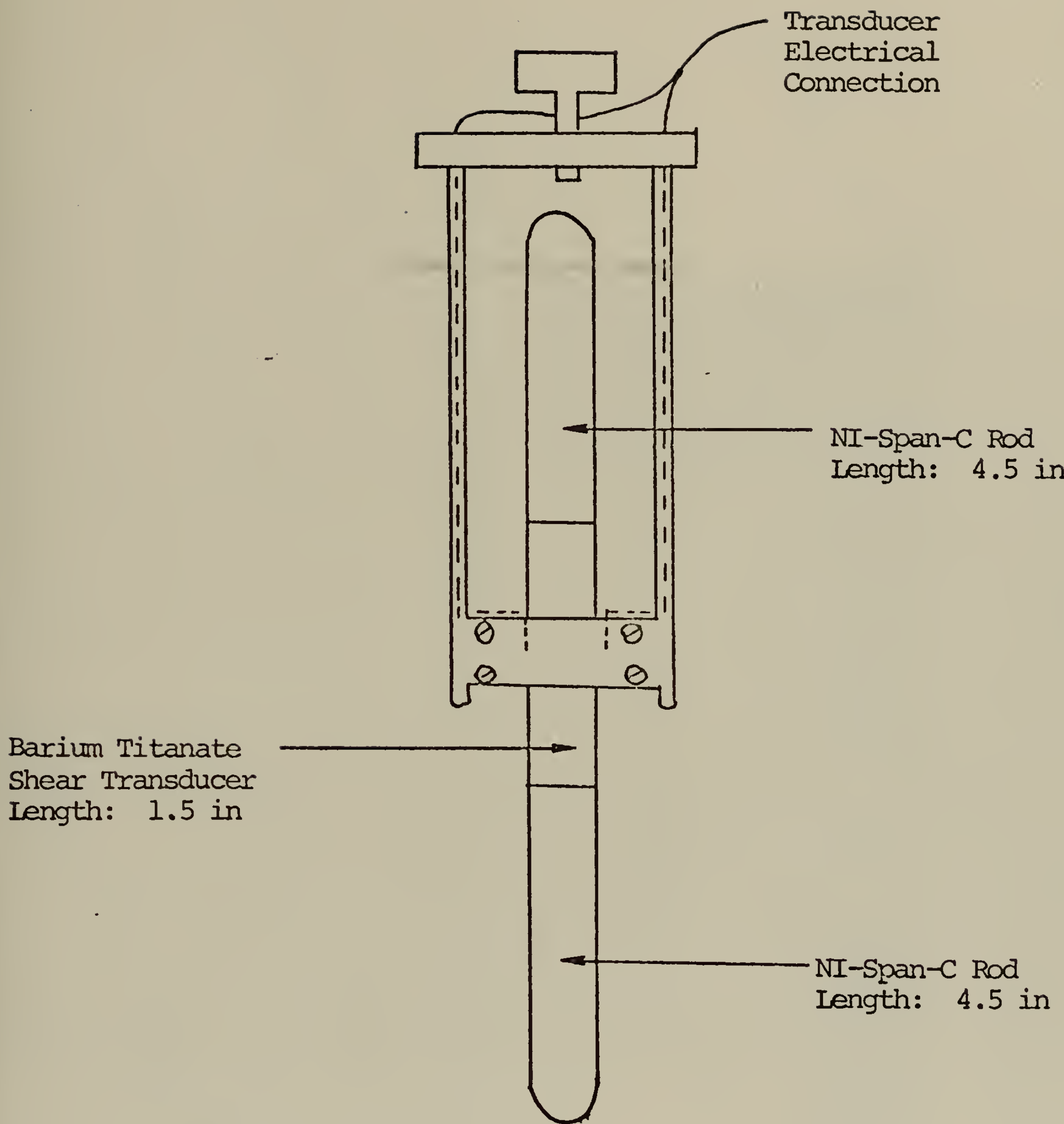

Figure 1. The Viscoelastometer

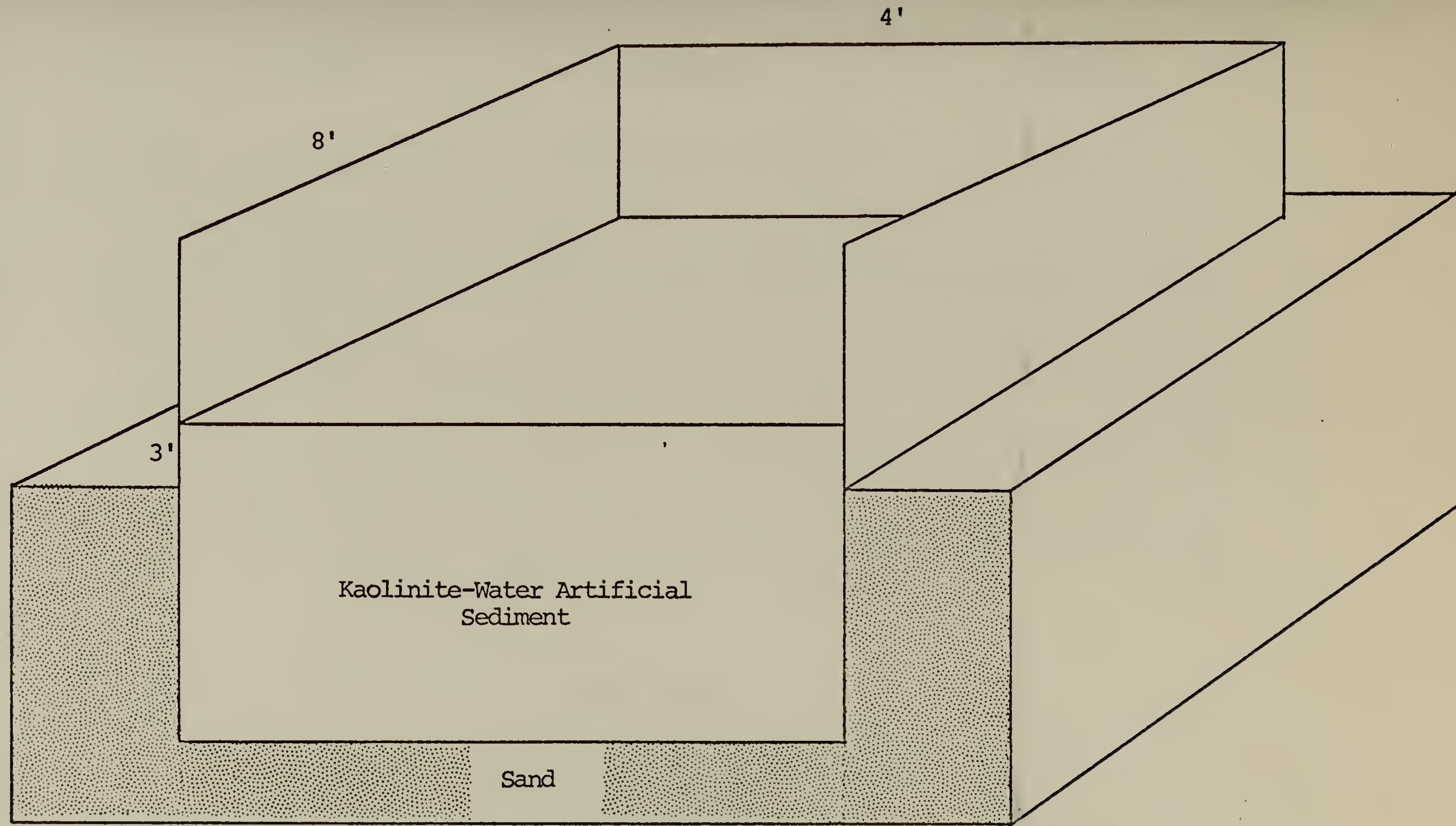

Figure 2. Cross-Sectional View of the Tank

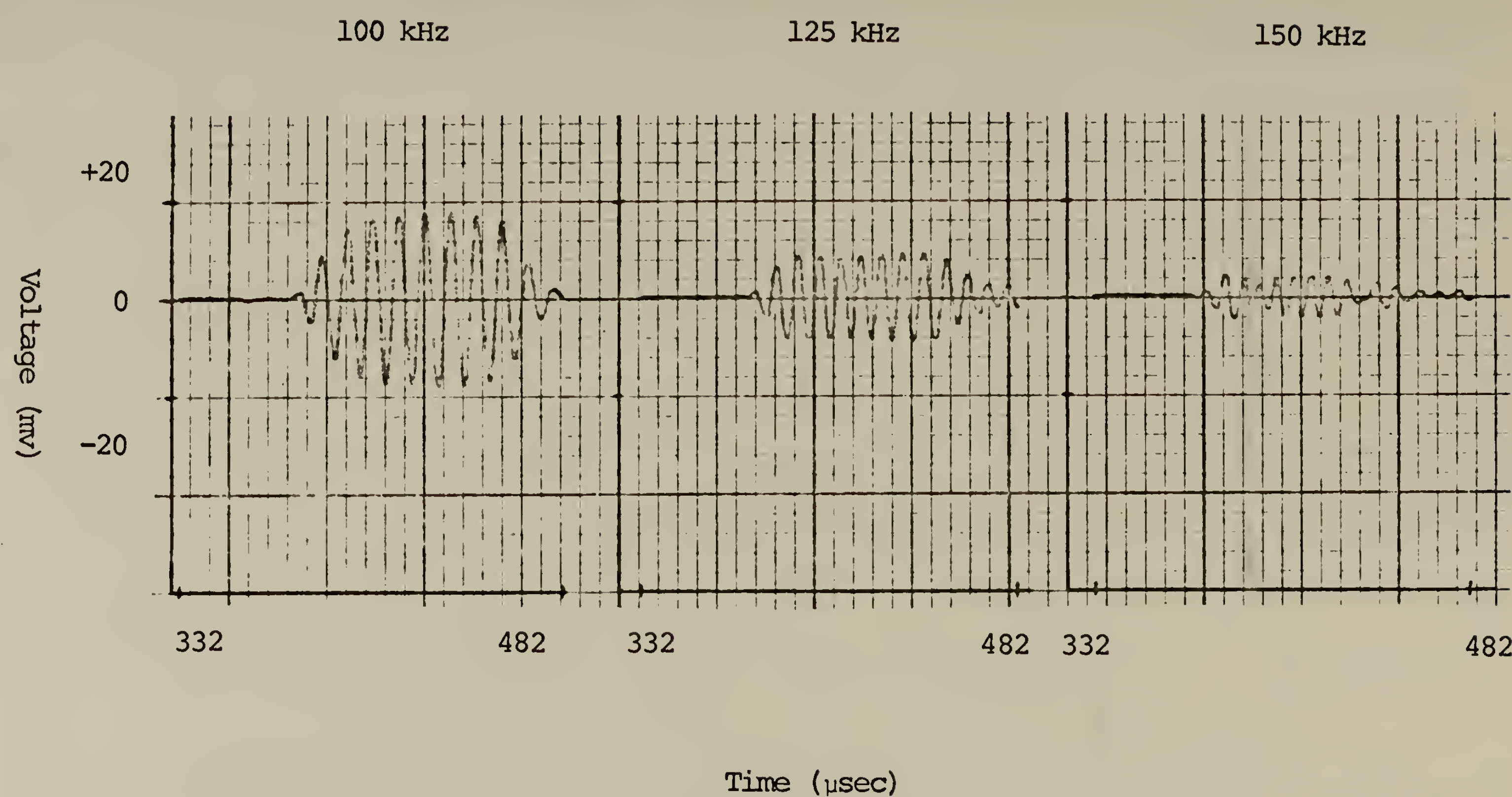

Figure 3. Received Signal Waveform Record.
Transducer-Hydrophone Separation: 50 cm.
Scan/Delay: 30%/45%.
16 μsec delay time has been added to time scale.
Time scale can be linearly interpolated.

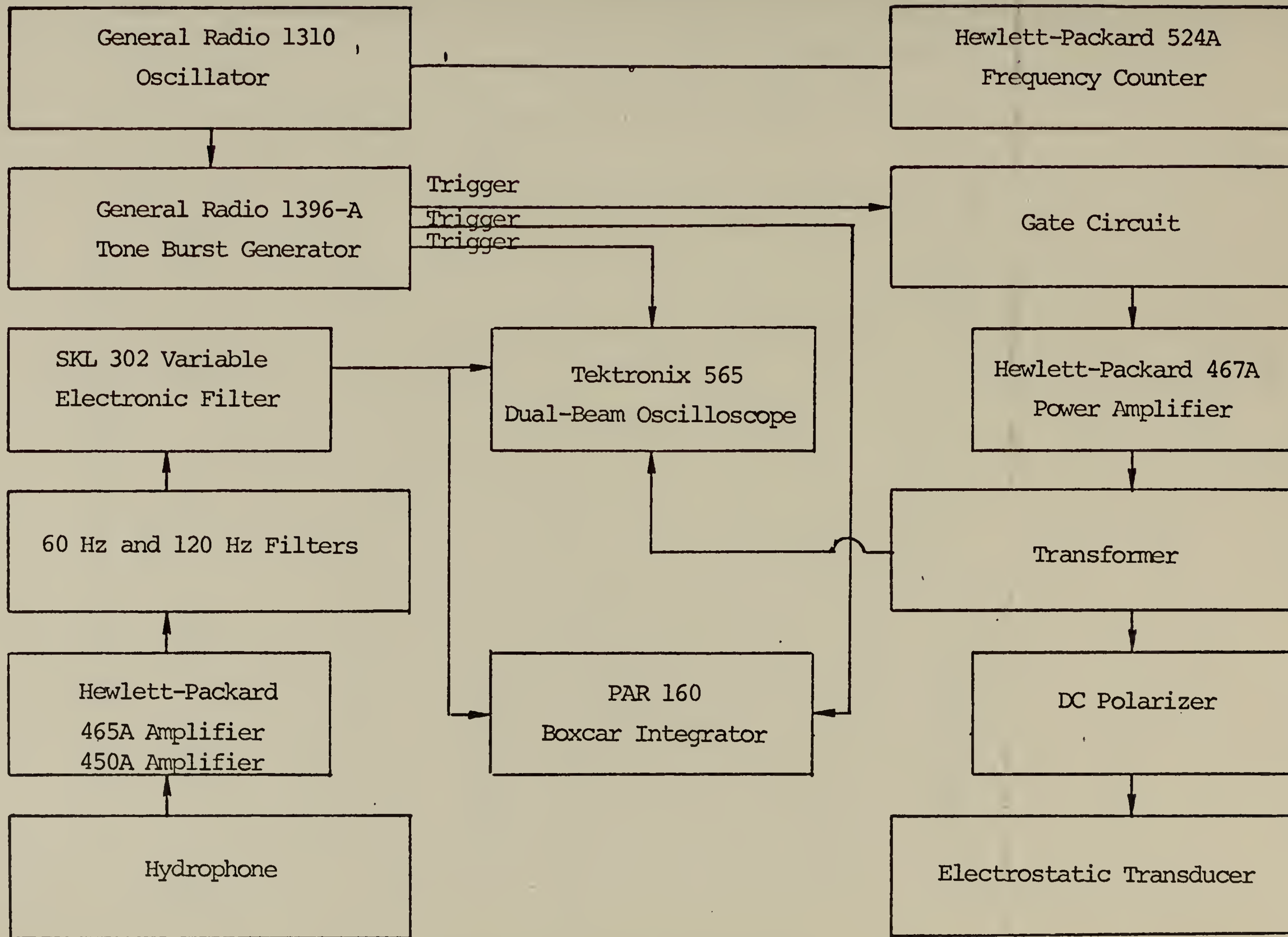

Figure 4. Block Diagram for Compressional Wave Measurements

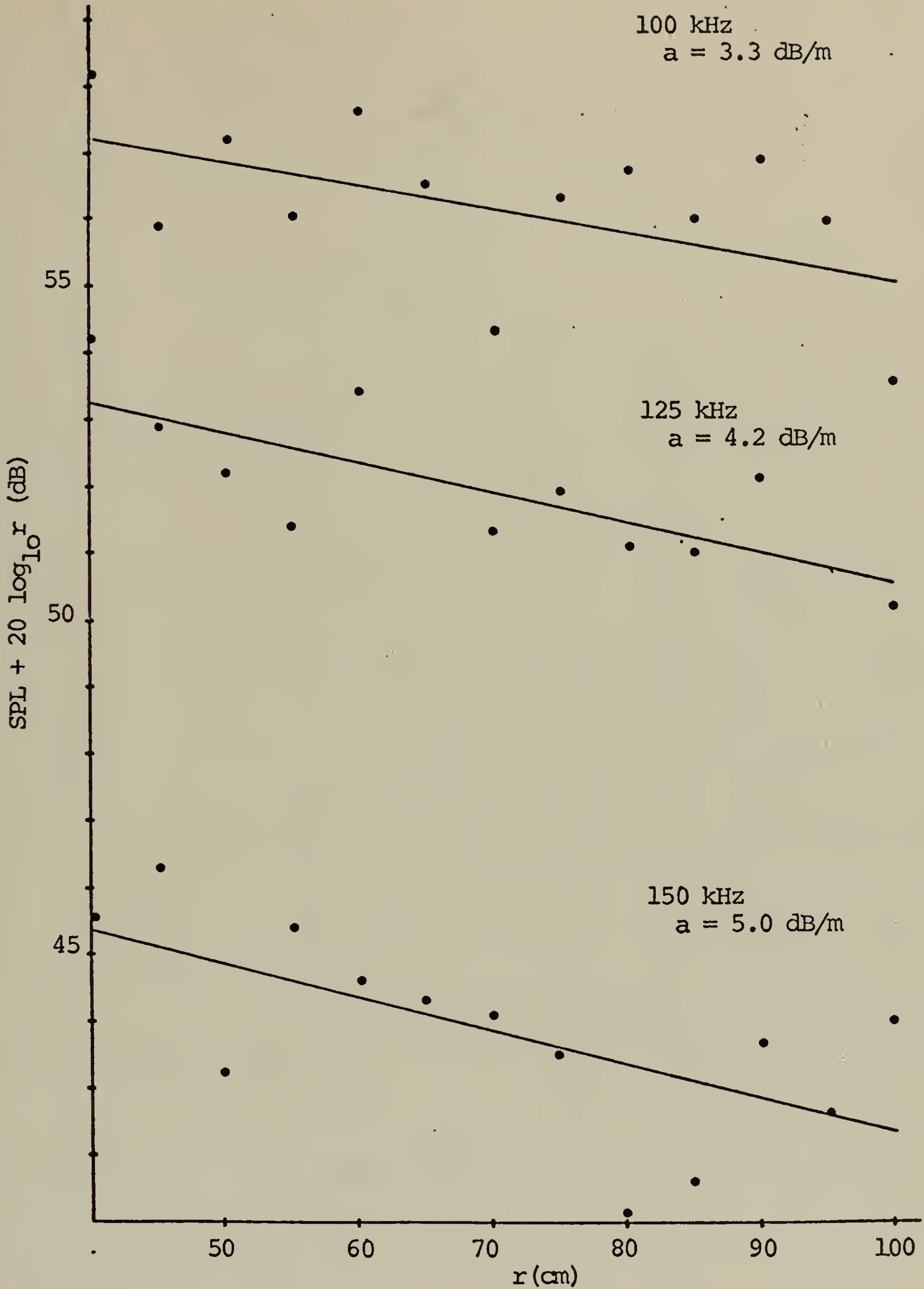

Figure 5. Plot of SPL + 20 $\log_{10} r$ vs Range (r)

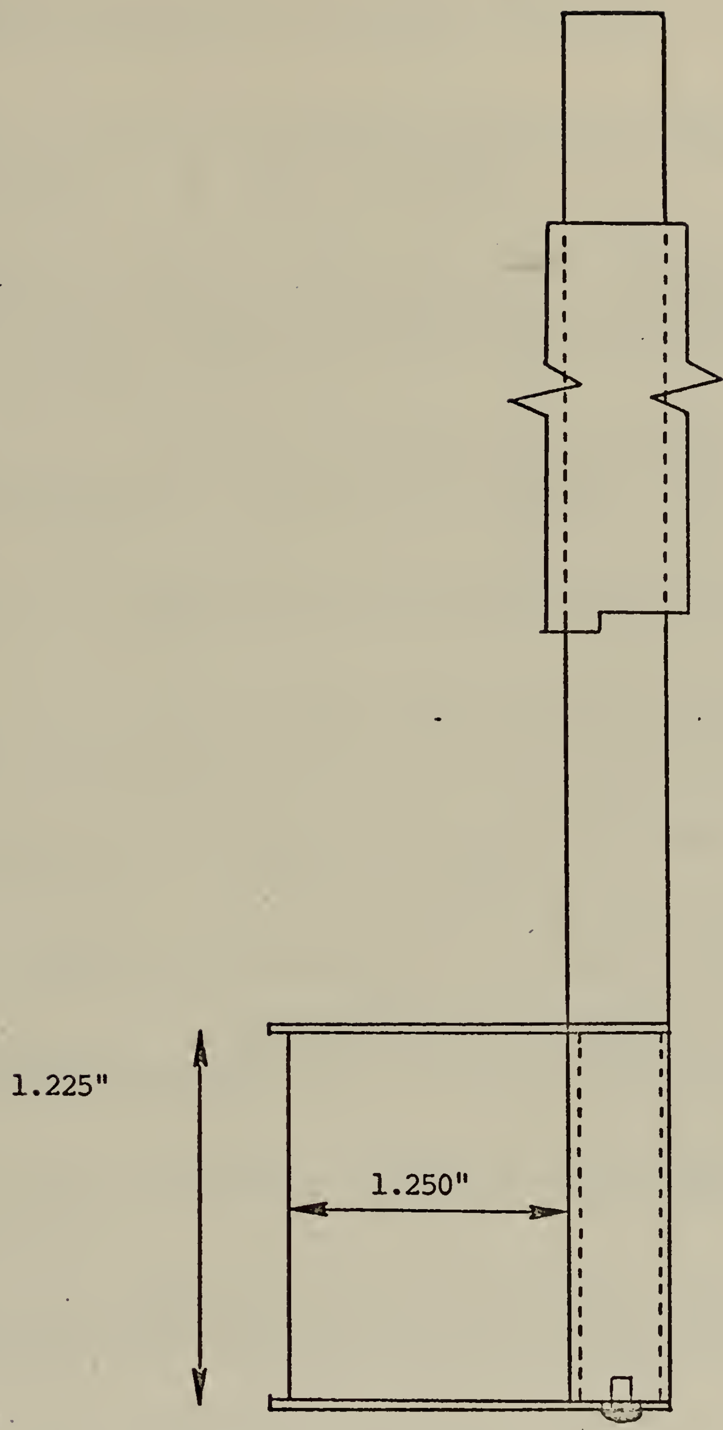

Figure 6. Sediment Sampler

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13. ABSTRACT

The absorption coefficient for compressional waves in a water-saturated, kaolinite clay was measured in the frequency range 100 to 150 kHz using a pulse technique with spherically diverging waves. The measurement also permitted determination of the sound speed, V_D. For one condition of the clay with a 77% porosity, the sound speed was 1422 m/sec. The absorption coefficient, a, was found to be frequency dependent, satisfying the empirical relationship a = 0.033 f dB/m, f being the frequency in kHz. No dispersion of wave speed with frequency was observed. These results were used together with the results of dynamic shear (rigidity) modulus measurements made with a torsional wave viscoelastometer to calculate the complex Lamé constants of a viscoelastic model.

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