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Ultrasonic characterization of marine sediments: a preliminary study

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Abstract

Ultrasonic waves (1 MHz and 2.25 MHz) were used to identify fluid mud and partially consolidated fine-grain sediment beds. The preliminary laboratory results indicate that both fine-grain sediments and coarse-grain sediments display distinguishable properties in terms of acoustic wave speed and attenuation rate. This approach can clearly detect the water–sediment interface with high resolution. It can also distinguish the consolidation status for a fine-grain sediment bed. Although the ultimate goal of measuring the vertical bulk density profile of a sediment bed still depends on more studies, the preliminary results are encouraging and indicate a new feasible method for field applications. © 1997 Elsevier Science B.V.

Keywords: bulk density; fluid mud; sediment properties; acoustic wave speed; acoustic attenuation

1. Introduction

Fluid muds and soft beds in estuaries, bays, and near-shore waters are interesting subjects for study (Nichols et al., 1978; Wells, 1983; Kirby, 1986). Here, a fluid mud refers to a high concentration near-bed suspension of cohesive sediment, and a soft bed refers to newly deposited sediment. The former has a sediment concentration from 10 to 100 g/l, and the latter typically has a concentration greater than 100 g/l. This is just a crude classification because the fluid mud properties are contingent upon many parameters (Mehta, 1983; Kirby, 1986). As expected, a fluid mud layer can contribute significantly to the total load of suspended sediment (Wells et al., 1978; Wells, 1983) despite the small thickness (less than a few centimeters) of this layer when compared with the total water depth.

In order to identify fluid muds and/or soft mud beds, various approaches have been attempted. For example, using an echo sounding device with dual-frequency, Parker and Kirby (1982) were able to identify a thick (on the order of meters) fluid mud layer. That approach, however, does not have high enough resolution to identify thin layers (on the order of centimeters or less) of fluffy mud, which are quite common in estuaries (Maa et al., 1996).

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The most straightforward approach to address the above problem would be to measure the vertical profile of bulk density. If the bulk density is less than a specific value, e.g., 1.4 g/cm^3 (1400 kg/m^3), it can be concluded that it is not a fully consolidated bed. Using a frozen core, Parchure and Mehta (1985) took samples from a laboratory annular flume to measure the vertical bulk density profile. This method has also been extended for field applications. The drawbacks of this method are that (1) the process is time-consuming, and (2) the accuracy is limited by the changing volume caused by the freezing process.

Measurement of the attenuation of X-rays (or Gamma rays) across a given distance in a mud bed is another approach for obtaining the density profile (Hirst et al., 1975; Kirby, 1988). This approach prevailed during the past two decades because, with the proper calibrations, it provided a quick identification of fluid muds and soft mud beds. To use this method, however, caution must be observed because of the natural radiation of X-rays. This method may also cause environmental concerns if the instrument is lost during an operation. Finally, the operating cost is also relatively high.

All of these drawbacks have provided an impetus for creating alternative methods. Replacing X-rays with ultrasonic waves is one such new approach (Verbeek and Cornelisse, 1995). An ultrasonic system does not carry the same safety concerns and potential environmental hazards. If the acoustic wave properties of marine sediments, especially of the soft, partially consolidated fine-grain sediments, are thoroughly understood, this method can also provide a quick and accurate characterization of fluid mud and soft mud bed properties, e.g., bulk density, sediment grain size, etc.

Recently, Mehta et al. (1995) used a low frequency (1.8 kHz) acoustic shear wave device to identify the change of shear modulus of the mud bed in a laboratory wave flume. They addressed another important parameter (shear modulus) assuming the mud bed was a Voigt viscoelastic continuum (Maa and Mehta, 1988). In their approach, however, the bulk density of mud was measured by a traditional method using core samples.

In many laboratory and field experiments, a type-I erosion behavior ($E = \epsilon e^{-\lambda t}$, where E is the erosion rate, t is time, ϵ is the initial erosion rate, and λ is a rate constant) was observed which suggested that the critical bed shear stress for sediment erosion, $\tau_c(z)$, increases with depth (Yeh, 1979; Parchure and Mehta, 1985; Maa et al., 1996; Maa and Lee, 1997). To find the vertical profile of $\tau_c(z)$, however, a high resolution profile of bulk density, $\rho(z)$, is needed. Details of the reasons and the procedures to construct $\tau_c(z)$ can be found in Parchure and Mehta (1985).

At the Virginia Institute of Marine Science (VIMS), we believe that the acoustic approach is the best method for conducting in situ identification of fluid muds and newly deposited beds. For this reason, we carried out the following experiments of which the preliminary results are presented to foster the development and application of this technique.

2. Experiments and apparatus

Two experiments were conducted: (1) a micro-scale consolidation test, and (2) a consolidation column test. The first test was designed to determine the feasibility of obtaining high resolution (2 mm) measurements of sediment properties, e.g., bulk density, near the water–sediment interface using an ultrasonic approach.

To meet this high resolution requirement, we selected a pair of the smallest acoustic transducers commercially available (Panametrics, model V133RM, 2.25 MHz, sensor diameter = 0.64 cm). The sensors were mounted diametrically facing each other on the tips of a fork-like probe (Fig. 1). One served as the source of acoustic waves and the other served as the receiver. The distance between these two sensors was 2.540 ± 0.003 cm. The probe was driven into sediment 0.2 cm per step using a step motor. This combination of transducer size and step size may not be small enough to obtain high resolution measurements, but improvements (e.g., acquiring a smaller transducer; or using a small wave guide) can be made at a later stage.

The sediment was obtained from the

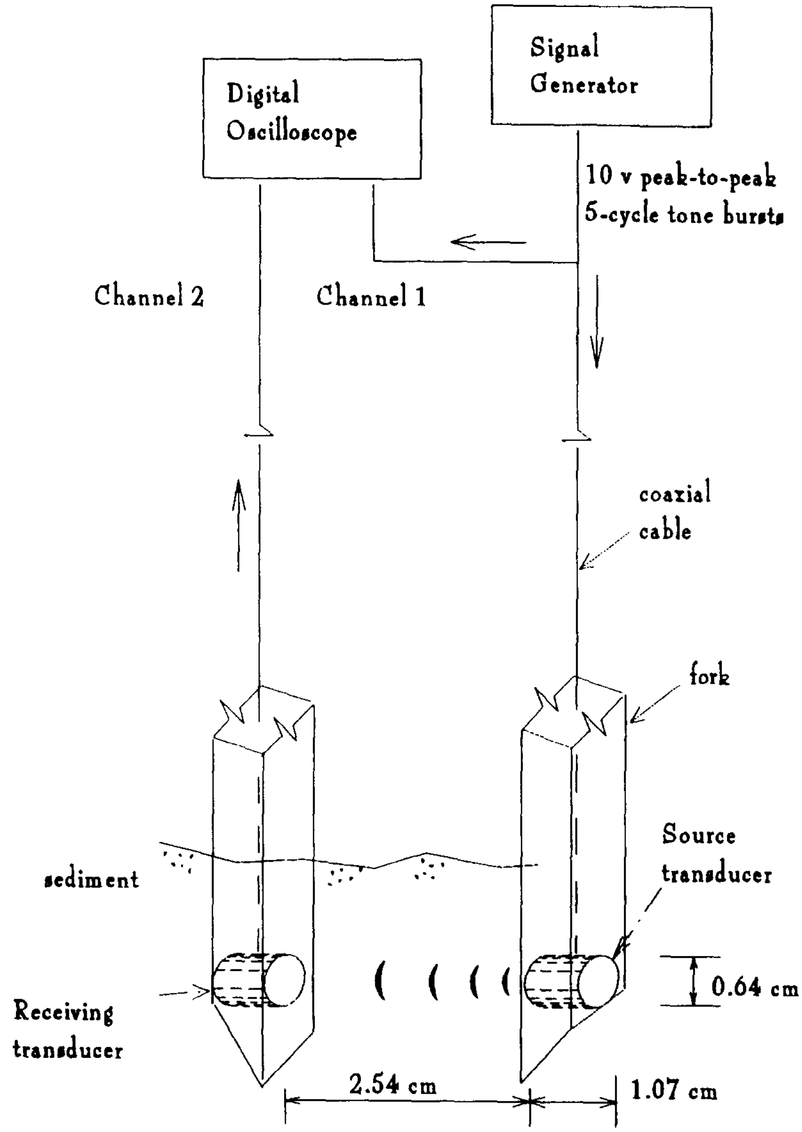

Fig. 1. Experimental set-up for measuring acoustic wave speed and attenuation in the micro-scale test.

Cherrystone site in the lower Chesapeake Bay (Maa and Lee, 1997). The sediment was mixed thoroughly with tap water in a 500 ml beaker and then deposited for selected times before each test.

Other instruments used in this experiment included a signal generator (Stanford Research System, model DS340), a digital oscilloscope (LeCroy, Model 9310), and a driver to move the probe into the sediment (Fig. 1). The signal generator provided repeated electrical signals of 5-cycle 2.25 MHz tone bursts (see the top window in Fig. 2), which were 10 V, peak-to-peak, to a 50 Ω load. Although the signal burst was periodic, only one burst was needed to measure the signal attenuation and wave speed. The signals were strong enough to excite the transducer, generating acoustic waves which passed through the sediment, picked up by the receiving transducer. The input excitation signals and the received signals were both recorded in the digital oscilloscope. The

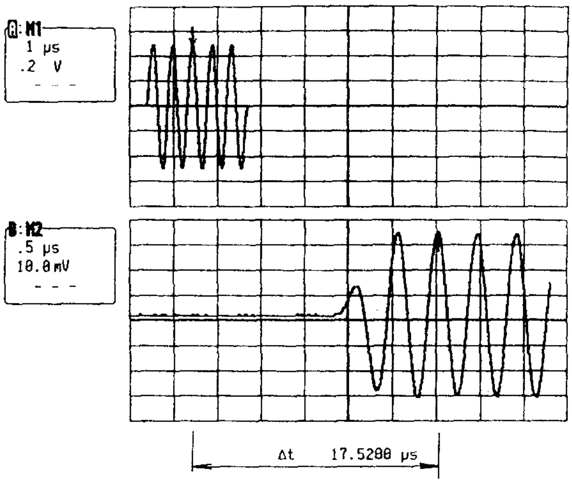

Fig. 2. An example of input signals (top) and received signals (bottom) recorded in the digital oscilloscope.

received signals were weak (less than 60 mV, see the bottom window in Fig. 2) because of internal friction energy loss. The time required (17.520 μs, see Fig. 2) for the signals to travel across the sediment was also measured using the oscilloscope.

The wedge shape at the fork tip helps to minimize the disturbance of sediment. For intrusive measurements, this is the best we can do. Of course, the small sensor size also helps.

The consolidation column test was designed to determine whether the changing status during consolidation can be acoustically determined. To address this issue, a well-mixed sediment slurry was placed into a Plexiglass tube (I.D. = 9.90 cm, O.D. = 11.38 cm, and length = 150 cm) to simulate the consolidation process that could possibly occur in nature, e.g., disposal of dredged material. This sediment was also from the sample acquired at the Cherrystone site. It was mixed thoroughly with seawater before pumping into the tube.

Because the acoustic waves needed to pass a much longer distance (11.38 cm) in this test, 1 MHz waves were selected to reduce the energy loss caused by internal friction. Two 1 MHz transducers (Panametrics, model 103RM, sensor diameter = 1.3 cm) were used in this experiment. They were mounted on a collar which could move along the Plexiglass tube and remain fixed in position at any selected elevation. Thus, the alignment and relative positions of the two transducers could be maintained for all the measurements. Also, signals of 5-cycle 1 MHz tone bursts (1 V, peak-to-peak) were generated and amplified to obtain a much higher power output (about 100 V at 50 Ω output load) for exciting the transducer. Both the input and received signals were also recorded in the oscilloscope. For these non-intrusive measurements, the sediment was not disturbed.

The calculations of wave speed were adjusted to remove the effects of a much higher wave speed in the Plexiglass wall. The wave attenuation measurements, however, were not modified because we are not asking for the absolute rate of energy dissipation at this time.

A pressure transducer (maximum 5 psig with an accuracy of 0.1% of the maximum reading) was mounted on the side at the bottom of the tube to measure the density of sediment slurry that was pumped into the column. It also monitored the change in total pressure caused by the sediment and water. The pressure signals were fed into an analog to digital conversion (A/D) interface card in a personal computer for recording.

To examine the sediment grain size distribution in the consolidation column test, four samples were taken after the experiment. Their locations are: (1) within the top 1 cm of the sediment column; (2) at 15 cm below the first sample location; (3) between the sediment–sediment interfaces (explained next); and (4) at 10 cm below the third location. The sediment samples were wet sieved through a 4 ϕ mesh sieve to separate sand and mud fractions, see Table 1. The sand fraction was analyzed using the VIMS Rapid Sand Analyzer (Byrne et al., 1982) and the mud fraction was analyzed using a Sedigraph. The results were merged to obtain the distribution of dispersed grain size. Unfortunately, no sediment grain size

Table 1
Grain size distribution

Location	Sand (%)	Silt (%)	Clay (%)	D_{50} (μm)
Top	11.78	27.35	60.87	0.9
Upper	6.83	33.91	59.26	1
S–S interface	22.19	61.63	16.19	32
Bottom	1.37	95.08	3.55	45

data is available for the micro-scale consolidation test.

3. Results and discussion

Although more studies are needed to fully address the feasibility of using this method to measure the bulk density of sediment bed, the preliminary results are encouraging and presented next.

3.1. Micro-scale tests

The acoustic wave heights attenuated sharply at the water–sediment interface (see Fig. 3). In this figure, the water–sediment interfaces for all three consolidation periods (1 h, 49 h, and 528 h) were brought together to show the similar significant gradient. As expected, the ultrasonic waves lost more energy in the sediment than in the water. Within the bed, however, the attenuation of acoustic waves varied significantly for the three consolidation periods. For the bed with an 1-h consolidation, there was a second sharp gradient of acoustic wave height between 2 and 2.5 cm below the water–sediment interface. This second high gradient indicated another interface within the sediment bed. In other words, the sediment bed could be further divided into a top sediment layer and a bottom sediment layer. The relatively large received acoustic wave height (Fig. 3) and low speed in the top sediment layer (Fig. 4) were probably due to a high void ratio within this layer.

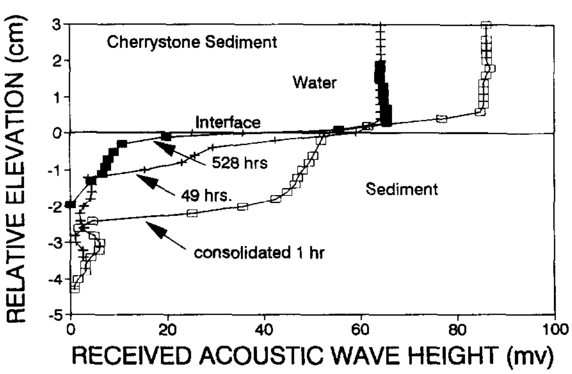

Fig. 3. Received acoustic wave height from the micro-scale test.

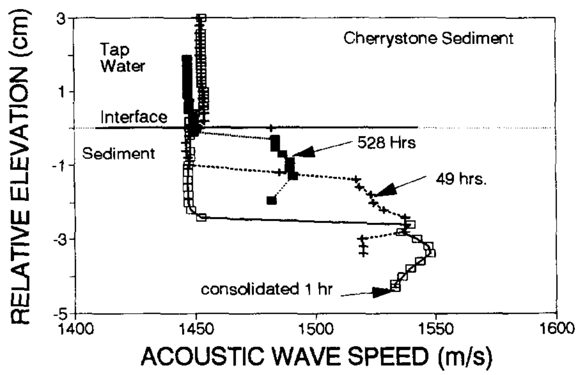

Fig. 4. Acoustic wave speed from the micro-scale test.

In the bottom sediment layer, the weak signal height (or high attenuation rate) and high speed were probably caused by a relative abundance of coarse sediment.

In general, the attenuation of acoustic waves in the sediment increased with the duration of consolidation, see Fig. 3. After 49 h of consolidation, the thickness of the top sediment layer decreased to approximately 1 cm. After 528 h, it almost disappeared. The decreasing thickness of the top sediment layer can be attributed to the decrease of the void ratio with time.

After 1 h deposition, the water layer still had a high suspended sediment concentration, and thus, small acoustic wave attenuation. The mechanism behind a low acoustic energy dissipation in turbid water, however, is not clear, and is beyond the scope of this study. The water layer was clean to the naked eye for the consolidation periods of 49 h and 528 h. Thus, the wave height attenuation was almost the same in the water column.

In the water layer, wave speed was slightly higher for the first two consolidation periods (1 h and 49 h), see Fig. 4. The speed was slightly slower for the 528-h-consolidation period. The difference, however, was less than 0.5% and may not be significant.

Within the bed, the wave propagation speed was significantly slower in the top sediment layer (even slower than that in water); see the two short consolidation periods in Fig. 4. This might be because the top sediment layer behaved as a visco-elastic material with small elasticity and high viscosity before full consolidation. After 528 h, the elasticity and speed both increased. The speed, however, was still smaller than that in the bottom sediment layer, see Fig. 4. This might be because the increase in elasticity, even after 528 h, was not enough to compete with the high speed of coarse sediments which should be abounding in the bottom sediment layer. In the bottom sediment layer, the consolidation process only reduced the void ratio slightly, and thus, changed the speed only slightly.

The pattern of speed and wave height profiles are quite similar, see Figs. 3 and 4, and may be used to identify the change of void ratio, or other soil properties (e.g., shear modulus and viscosity).

3.2. Consolidation column test

Four phases of consolidation can be identified in this test, see Fig. 5. For the first 10 h (phase 1), the water-sediment interface drops very fast. Between 10 and about 50 h (phase 2), a semi-log relationship between the elevation of sediment-water interface and time can be established. This indicates an exponential rate of consolidation, with the rate remaining constant in phase 2. This rate changed slowly in phase 3 (between 50 and 150 h), and again, remaining constant, in phase 4 (after 150 h).

Vertical profiles of the received acoustic waves for this test are plotted in Fig. 6 for selected consolidation durations. The results are plotted

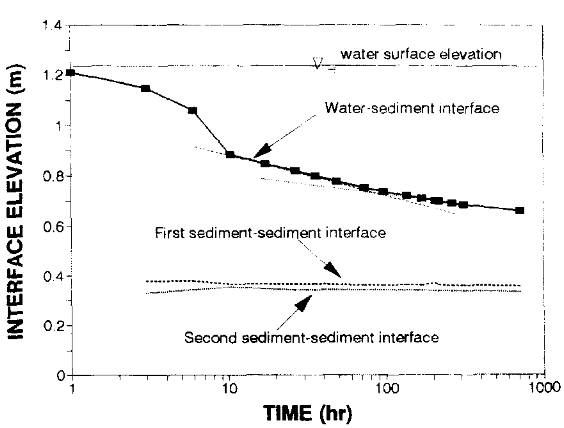

Fig. 5. The change of interfaces elevation from the consolidation column test.

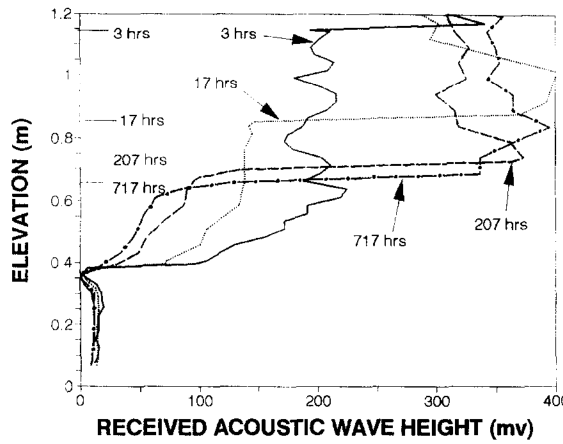

Fig. 6. Received acoustic wave height from the consolidation column test.

with a reference selected at the bottom. The visually observed water-sediment interfaces for those selected durations are marked on the ordinate of this diagram. Like the micro-scale test, the water-sediment interfaces are easily identified by a significant gradient and large difference in acoustic wave height. Below the water-sediment interface, the received signals were further reduced with a moderate gradient and reaching a minimum that was close to zero from 0.34 m to 0.38 m. This indicated a layer with a high acoustic energy dissipation rate. Further downward, the received signals became stronger (on the order of 20 mV), but the changes in received signals were minimal. This behavior contrasted with that shown in the top sediment layer.

In summary, there were three sediment layers with two sediment-sediment interfaces at 0.34 m and 0.38 m. The high attenuation in the middle sediment layer might be caused by an appropriate ratio of sediment grain size to acoustic wave length. More studies, however, are needed to fully address this possibility.

Locations of the two sediment-sediment interfaces are also shown in Fig. 5. The borders of these two interfaces are defined as the region in which the received acoustic wave height is less than 5 mV (see Fig. 6). Notice that the elevation of these two sediment-sediment interfaces only changed slightly during the entire 720-h-experimental period, which indicates that the consolidation process for the bottom sediment layer was nearly completed shortly after the onset of this test.

With respect to wave speed, four zones can be identified for the entire column, see Fig. 7. Starting from the top, the first zone was water with a speed about 1450 m/s. The second zone was partially or fully consolidated fine-grain sediment with a typical speed of about 1430–1440 m/s (slower than that in water). The third zone was between the two sediment–sediment interfaces with a sharp gradient in speed. The fourth zone was the coarse sediment below the second sediment–sediment interface with an average speed of about 1580 m/s. The thickness of the first two zones changed drastically with time, especially for the first 200 h. The speed, however, only changed slightly within these two zones. Notice that the speed was always slower in the second zone probably because of the high content of fine-grain sediment and its viscoelastic properties (Hamilton, 1969). The speed was much faster in the fourth zone (1580–1600 m/s). In comparison with the speed obtained in the micro-scale test (about 1530–1550 m/s, see Fig. 4), the speed in the bottom layer of the consolidation column test is marginally higher (about 3%). This may be attributed to the difference in sediment components and water (tap water versus seawater) between these two tests even though the two sediments both came from the same sample. In the micro-scale test, only a small amount (about 200 ml) of sediment was taken from the top of the sample, and thus, the percentage of coarse material in the bottom sediment layer may be smaller than that for the consolidation test. In the consolidation column test, approximately half of the sample (about 4000 ml) was used. Thus, the percentage of coarse material in the bottom sediment layer may be higher.

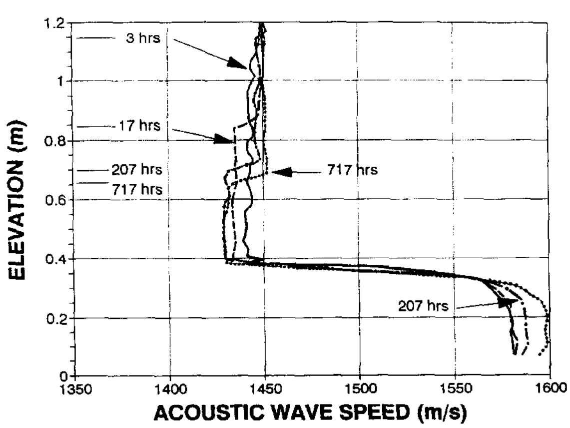

Fig. 7. Acoustic wave speed from the consolidation column test.

The main purpose for measuring the pressure at the bottom of the consolidation column is to obtain the density of the sediment slurry, or the suspended sediment concentration of slurry when first placed into the column. The change in pressure with time (Fig. 8), however, also reveals an interesting process for the development of a sediment skeleton. The output of the pressure transducer is measured in volts (V), which can be converted to height-of-water-column, h, using the calibration equation obtained before the consolidation experiment: $V = 1.44107h - 0.00033$. When the water is substituted with the well-mixed sediment slurry, h should be replaced with ρh to incorporate the effect of increasing density. Thus, with an initial height of 1.246 m (see Fig. 5), the density of the sediment slurry that was placed into the column can be estimated as 1.285 g/cm^3.

The pressure decreased quickly in the first hour, and then continuously decreased at a much slower rate. The decrease in pressure is due to the build-up of a sediment skeleton during consolidation. Between 100 and 380 h, there was a relatively fast rate of decrease in pressure caused by a combination of consolidation and the evaporation of water from the column. When water was added to bring the water level back to the original level at 380 h, the pressure jumped back. Thus, the true change

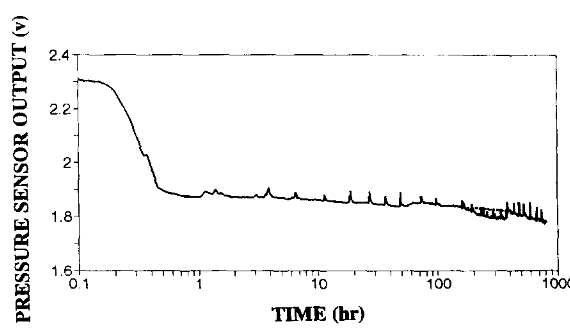

Fig. 8. Pressure variation at the bottom of the consolidation column.

should be represented by the dashed line shown in the figure. There are many spikes in this figure. The cause of these spikes is not yet clear. They are probably electrical noises captured by the A/D interface card. Nevertheless, the spikes do not hide the development of a soil skeleton.

The grain size distributions of the four samples taken from the consolidation column test (Fig. 9) indicate that the top two samples are very similar, with a composition of 59% to 61% of clay and 27% to 33% of silt. Table 1 shows the composition of these four samples. Notice that the clay content steadily decreases from the top to bottom samples. Between the sediment–sediment interfaces, there exists a relatively high content of sand, which may be the reason for the high dissipation rate of acoustic energy.

Wave lengths for the two frequencies used in the tests (1.0 MHz and 2.25 MHz) are about 1500 μm and 660 μm, respectively. These lengths are much larger than the grain size of clay (less than 2 μm) and silt (up to 60 μm). It is also much larger than the grain size of very fine sand (60 to 125 μm) and fine sand (125 to 250 μm). The grain size analysis of sediment samples used in the experiments, see Table 1, indicates that the majority of sediment is silt and clay. Thus, the energy dissipation of acoustic waves in these two experiments is mainly caused by internal friction, which includes all the possible mechanisms for energy dissipation other than wave scattering. The possible energy loss caused by wave scattering (which becomes important when dealing with coarse material, e.g., medium-grain sand, 250 to 500 μm, and coarse-grain sand, 500 to 1000 μm) is unlikely in these two experiments.

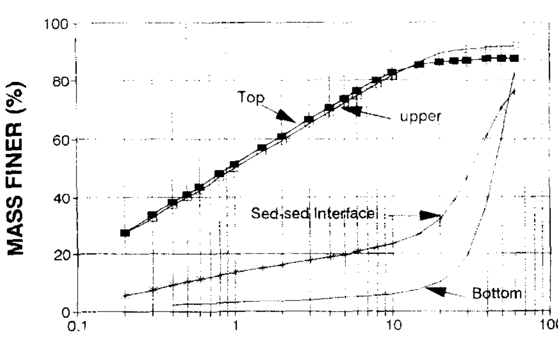

Fig. 9. Grain size distribution at selected elevations from the consolidation column test.

3.3. Future experiments

It is important to understand that the primary mechanism for acoustic energy loss is caused by internal friction for most marine sediments. This is because the surficial sediments are mainly fine-grain sediments. The following expression, $H = H_0\ e^{-\beta x}$, may be used to describe the energy loss, where H_0 is the acoustic energy at the source, H is the acoustic energy at a distance x from the source, and β is the attenuation coefficient. Our data indicated that each sediment grain size has a different internal friction coefficient. This coefficient also changed with the duration of consolidation, i.e., $\beta = \beta$ (grain size, duration of consolidation). The importance of consolidation duration decreases as the sediment grain size increases. For coarse sediments, this influence is small because of the fast pace of consolidation, but this influence can be quite significant for fine sediments. If β could be clearly determined, the bulk density of a sediment can be calculated. For this reason, a series of calibration experiments is needed to find the attenuation coefficient.

For calibration, one needs to know the sediment grain size as well as the bulk density, which may represent the status of consolidation. To meet this criterion, we can prepare several sediment samples with nearly uniform grain size and known initial concentrations. These samples can then be placed in test tubes with a carved volume scale. After consolidating the selected durations in these test tubes, one can estimate the bulk densities by observing the volume changes. Knowing the bulk density, grain size, acoustic wave speed, and the attenuation coefficient, a relationship may then be established serving as the first step for calibrations.

Similar experiments for a mixture of several size classes of sediments, as well as a mixture of cohesive and non-cohesive sediments, should also be carried out as the second step for calibrations.

Modifying the laboratory experiment facility for field uses is a relatively straightforward matter. A device similar to that built for the micro-scale consolidation test can be enhanced for field uses. The signal generator and oscilloscope will be on board a research vessel, and thus, require no modification at all. An underwater unit is needed to hold all other instruments for field deployments. Two coaxial cables will be used to connect the on-board unit and the underwater unit. The underwater unit may include: (1) a water-resistant cylindrical box to house the driving step motor and gear head; (2) a self-contained instrument amplifier unit to boost the received signals for long-distance transmission; and (3) a small tripod for mounting all the gears. The probe may also need to be redesigned to house selected commercially available underwater transducers of which there are plenty on the market. A special type can also be ordered because Nondestructive Testing (NDT) is a well established industry.

4. Conclusions

Two laboratory experiments were carried out to determine if ultrasonic waves can be used to identify the water–sediment interface and to monitor the process of consolidation. The preliminary conclusions of these two experiments are summarized below.

(1) At the water–sediment interface, there is a sharp gradient of acoustic wave height. The difference in acoustic wave height above and below the interface is quite significant. This is a clear criterion for identifying the interface in field measurements.

(2) For a partially consolidated fine sediment, e.g., clay or silt, the attenuation rate of acoustic wave height is moderate. The speed of acoustic waves, however, is always lower than that in the overlying water. A possible reason for this phenomenon may be because of the low elasticity and high viscosity of cohesive, fine sediments.

(3) For coarse sediments, e.g., fine sand, the rate of acoustic energy dissipation is high. The wave speed is also high. This may be explained by the high rigidity of each particle and lack of binding force among particles in a coarse sediment. When the ratio of grain size to the acoustic wave length is close to certain values, the acoustic energy loss caused by wave scattering may also be important.

(4) In the micro-scale experiment, a clear sediment–sediment interface can be identified within the bed. This interface indicates a two-layer structure in the sediment bed. With time, the thickness of the top sediment layer diminishes.

(5) In the consolidation column test, two sediment–sediment interfaces can be identified which implies a three-layers bed structure. For the top fine-grain sediment layer, the change in acoustic wave height and speed with time is obvious because of the slow rate of consolidation. For the coarse bottom sediment layer, the change in acoustic wave height and speed with time is insignificant because of the fast rate of consolidation. The process was almost completed shortly after the onset of this experiment.

(6) Even for a high suspension sediment concentration (on the order of 1 g/l) in water, e.g., the 1-h-consolidation case in the micro-scale test, the difference in the received acoustic wave height and speed is very clear between the water and the bed. Thus, the acoustic approach is capable of distinguishing between sediments in suspension or sediments in the bed.

The above experimental results provided a base for developing a probe to identify the change in void ratio, bulk density, and sediment components. More experiments, however, are needed to further explore the characterization of supersonic waves in marine sediments.

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