

Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

Preston S. Wilson
Applied Research Laboratories
The University of Texas at Austin
P.O. Box 8029
Austin, TX 78713-8029
phone: (512) 475-9093 fax: (512) 471-8727 email: pswilson@mail.utexas.edu

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LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube methods, [1] in the frequency range of approximately 500 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. [2] These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [3-10] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation.

Initial impedance tube work [2] indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective was to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

A secondary objective, added by the program management to this project late this fiscal year, was for the PI to participate in the Shallow Water '04 experiment, specifically to provide and deploy the Combustive Sound Source [11] from the R/V Knorr.

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APPROACH

The impedance tube technique and has been adopted as a standard technique [12-14] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [1] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [15] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is ± 0.14 dB in magnitude and $\pm 0.8^\circ$ in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It will operate in the frequency range in which dispersion is expected (about 500 Hz to 30 kHz) in typical sandy sediments. We are investigating two new impedance measurement techniques [16, 17] that do not require movement of the sensors, and will minimize errors due to sensor position uncertainty. Further, we will incorporate new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling will be based on and extended from existing work for lossy fluid coupling in elastic waveguides, [17, 18] additional sample-wall boundary effects, [19] sample-fluid boundary effects [20] and asymmetric excitation. [21] The instrument will be used in the laboratory to investigate artificial and natural sediments *in vitro*.

In the final year of the project, we plan to modify the laboratory device for use on the ocean bottom for *in situ* characterization of sediments. There are two possible versions of the *in situ* device, and these were explored in an earlier study. [22] In one of the versions, the impedance tube will penetrate the ocean bottom and a reflection coefficient will be measured inside the tube. In the other version, the impedance tube will not penetrate the sediment, but will sit flush on the bottom. The impedance measurements can be made, regardless of the exact configuration and will contain information about the material properties of the ocean bottom. The interpretation of those measurements will require appropriate modeling. For example, the penetrating version could be modeled using the classic theory of Levine and Schwinger [23] for sound radiation from an open tube, in which the sediment sound speed would be a parameter. The flush-deployed version may be modeled with a finite-element numerical model such as described in [24], again with material properties as parameters. In both cases, the impedance measured by the impedance tube would be compared to the appropriate model and sediment parameters varied until measured and modeled impedances are in agreement. Additional modeling beyond that described in [23] and [24] is anticipated, to obtain useful inversions for material parameters in both cases, but the raw impedance measurements themselves may prove to be useful.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant Research Professor at the University's Applied Research Laboratories (ARL:UT). In addition to oversight, Wilson contributes significantly to many tasks, including modeling, instrument and experiment design, construction and operation. Paul A. Waters was an Undergraduate Research Assistant on the project from the start of the Fiscal year until 31 Dec. 2006. Waters served as an electromechanical technician and provided machine shop, procurement and software support, and

oversaw purchasing. Waters graduated and was replaced on 1 June 2006, by Ryan L. Renfrow, a UTME senior. Jacob G. Migliazzo was a Graduate Research Assistant on this project from the start of the fiscal year until 31 May 2006. Migliazzo left the project on 31 May 2006, for an internship at Bose. On 1 June 2006, Theodore F. Argo IV, a UTME Ph.D. student replaced Migliazzo and contributes to all aspects of the project.

WORK COMPLETED

Primary Objective—Laboratory Sediment Investigation: Construction of the impedance tube itself was completed this year, along with a support structure to hold the tube vertically and a scaffold to afford personnel access to the top of the tube. A variety of terminations were completed, including an air-backing chamber and a housing that holds a piston, for excitation from the bottom. The latter is in support of the new impedance measurement technique [17] mentioned previously that is being evaluated. This technique (referred to as the Mert method) may prove beneficial because it does not require any sensors to be placed inside the tube. Instead, excitation is provided at the bottom of the tube, via the piston previously mentioned, and force and acceleration is measured between the piston and the prime mover. The apparatus as it was at the beginning of the fiscal year is shown in Fig. 2. The apparatus in its current state is shown in Fig. 3, which also includes a schematic diagram of the Mert impedance measurement technique being evaluated. A Wilcoxon electromechanical shaker, equipped with force and acceleration sensors, and a pair of conditioning amplifiers were purchased and installed. A high accuracy A-D/D-A board was also purchased to provide a dedicated data acquisition for the project. LabVIEW software was acquired and programmed to operate the impedance tube system, in all of its various configurations. Impedance measurements using the technique shown in Fig. 2 were performed with distilled water and a reconstituted natural sand sediment. Preliminary results from the Mert method were also obtained on water samples, and water-saturated sand and glass bead samples.

An opportunity became available this FY (at no cost to this grant) to collaborate with the Seafloor Sciences Group at NRL-SSC on an experiment with gas-bearing sediments. An unprecedented set of contemporaneous acoustic measurements and computed x-ray tomography imaging scans were obtained on a variety of reconstituted natural sediments. These experiments were conducted at NRL-SSC in January 2006. A 1-D acoustic resonator technique was used to measure the sound speed inside the sediment samples. The imaging scans yielded the bubble size distribution and the total void fraction (gas content) of the sediment. This collaboration also yielded permeability measurements on a sand sample that had been the subject of a previous study. [25, 26] The new permeability measurement was a significant addition to the results and yielded a new interpretation of the data.

Secondary Objective—SW06 Experiment: The Combustive Sound Source (CSS), which had been dormant for 9 years, was recalled to service for the SW06 experiment. The following was undertaken to make the CSS ready for deployment from the R/V Knorr. An electrolytic hydrogen/oxygen generator was purchased and equipment was fabricated to inject gas into the CSS chamber while the CSS was deployed from the fantail A-frame of the Knorr. The original ignition box and cable were refurbished. A number of spark plugs were purchased, since they are somewhat consumable. A National Instruments data acquisition system was purchased and existing hydrophones were equipped with extension cables for use on the Knorr. All of the equipment was shipped to Woods Hole and loaded on the R/V Knorr on 22 August. The PI boarded the Knorr on 23 August and worked with the science team on many aspects of the experiments, in addition to deployment of the CSS. The PI departed the R/V Knorr on 5 Sept and returned to Woods Hole via the R/V Oceanus on 6 Sept 2006.

RESULTS

Primary Objective— Laboratory Sediment Investigation: Preliminary results from the new impedance tube system have been obtained and are shown in this section. This includes measurements with the original method and the new Mert method. Figs. 4 and 5 show the impedance of water-filled and water-saturated-sand-filled transmission lines made with the original method. A model prediction is shown for the water-filled case. Good agreement between measurement and model indicates a good understanding of the impedance tube system for liquids. The model predictions for the sediment cases have not yet been completed, nor have we extracted sound speed and attenuation yet. One can observe expected qualitative differences between Figs 4 and 5. For example, we expect the sediment to have a faster sound speed and higher attenuation than the water and those effects are visible. The peaks and troughs are less sharp in the sediment case, which indicates higher attenuation. They are shifted to a higher frequency in the sediment case, which indicates a higher sound speed. A typical impedance measurement for distilled water, obtained by the new Mert method, is shown in Fig. 6. Impedance tube measurements and data analysis will continue. Both methods used so far yield good agreement between measurement and prediction for a known sample material, distilled water. Further work is underway to invert material parameters for the sediment case, in which the sample/tube wall coupling is more complicated.

The collaborative work with NRL-SSC resulted in the measurement of sound speed of a reconstituted gas-bearing natural Kaolinite sediment. Contemporaneous measurements of the bubble size distribution were also attained. A single image from the tomography scan is shown in Fig. 7. From this data, the overall sample void fraction was found to be $\chi = 0.0045 \pm 0.001$. The density was also measured and found to be $\rho = 1581 \pm 1.58 \text{ kg/m}^3$. The acoustic experiment and the resulting sound speed measurement are shown in Fig. 8. This Kaolinite sample was very fluid-like, yet it could still suspend bubbles. It was found that the sound speed observed in the acoustic experiment was perfectly consistent with the sound speed predicted by Wood's Equation, which is a mixture rule for bubbly liquids, in which the sound speed depends only on the gas-free sediment bulk density and the void fraction. To the PI's knowledge, this is the first quantitative verification of Wood's Equation for a gas-bearing sediment.

Last year we reported on the analysis of a data set in which the sound speed of a water-saturated sediment was inferred from the measured resonances of a right circular cylinder shaped plastic tank filled with water-saturated sand. Figs. 9 and 10 describe the experiment and the details are described elsewhere. [25, 26] The permeability was not measured in the original experiment and a canonical value from the literature was used in the initial analysis. The data and the corresponding William's EDFM [10] prediction are shown in Fig. 11. Thanks to NRL-SSC, we now have a measurement of the permeability of the sediment and it differs from the canonical value, which results in much better agreement between the data and the EDFM prediction. The new permeability and the corresponding model curve are also shown in Fig. 11. It now appears that the data is very well described by the EDFM throughout the experimental frequency range. The significance is the following: This result supports the notion that the EDFM *does not* over predict mid-frequency sound speeds and that when free gas is absent from a water saturated sandy sediment, the EDFM correctly predicts the sound speed near the transition frequency and above.

Secondary Objective—SW06 Experiment: The CSS was successfully deployed from the R/V Knorr during SW06. On the order of 50 shots were delivered. In its current state of development, CSS

deployment and operation requires a crew of 5 and about 30 minutes between shots. Acoustically, the CSS is an excellent broadband/impulsive energy source, but the efficiency and speed of operation could be greatly improved. A typical shot is shown in Fig. 12. The usable frequency range of this shot is from 10 Hz to 5 kHz, with a peak energy spectral density of 170 dB re $1\mu\text{Pa}^2\text{-s/Hz}$ at 1m occurring at about 20 Hz.

IMPACT/APPLICATIONS

The Biot-based description of sound propagation within sandy marine sediments is gaining support in the ocean acoustics and related research communities, but we are also coming to the conclusion that it is not fully adequate. The current results indicate that the EDFM correctly predicts the mid and high frequency sound speed in water saturated sand. We are continuing our efforts to get low frequency measurements. As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems. A better description of bottom interaction will increase our ability to detect, localize and classify targets in littoral environments. The same can be said for buried objects. The CSS performed very well during SW06 and may prove to be a very useful tool for ocean acoustics experiments in the future.

RELATED PROJECTS

SAX99: Sediment Acoustics Experiment 1999

From the project web page: SAX99 addresses high-frequency sound penetration into, propagation within, and scattering from the shallow-water seafloor at a basic research (6.1) level.

<http://www.apl.washington.edu/programs/SAX99/Program/prog.html>

SAX04: Sediment Acoustics Experiment 2004

From the project web page: The overall objective of SAX04 is to better understand the acoustic detection at low grazing angles of objects, such as mines, buried in sandy marine sediments. One component of the SAX04 work is designed to collect data and gain a greater understanding of high-frequency sound penetration into, propagation within, and scattering from the shallow water seafloor at a basic research level. A second component is designed to provide data directly on acoustic detections of buried mine-like objects at low grazing angles.

<http://www.apl.washington.edu/projects/SAX04/summary.html>

Other ARL:UT sediment researchers: Marcia Isakson and Nicholas Chotiros both conduct research on sound propagation in marine sediments.

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PUBLICATIONS

P.S. Wilson, A. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," *J. Acoust. Soc. Am.*, (2006). [refereed, in press]

FIGURES

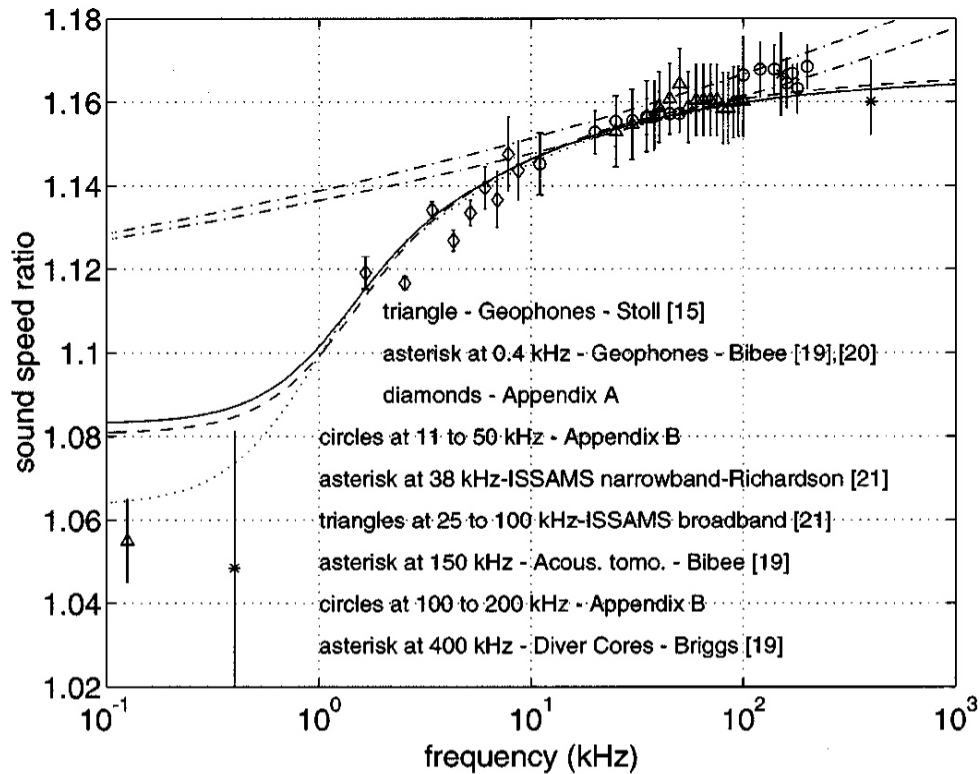


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [27]. The theoretical curves are: solid line=Biot/Stoll [9]; dashed line=Williams [10], dash-dot lines=Buckingham's model for two values of fluid viscosity [8]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [27].)

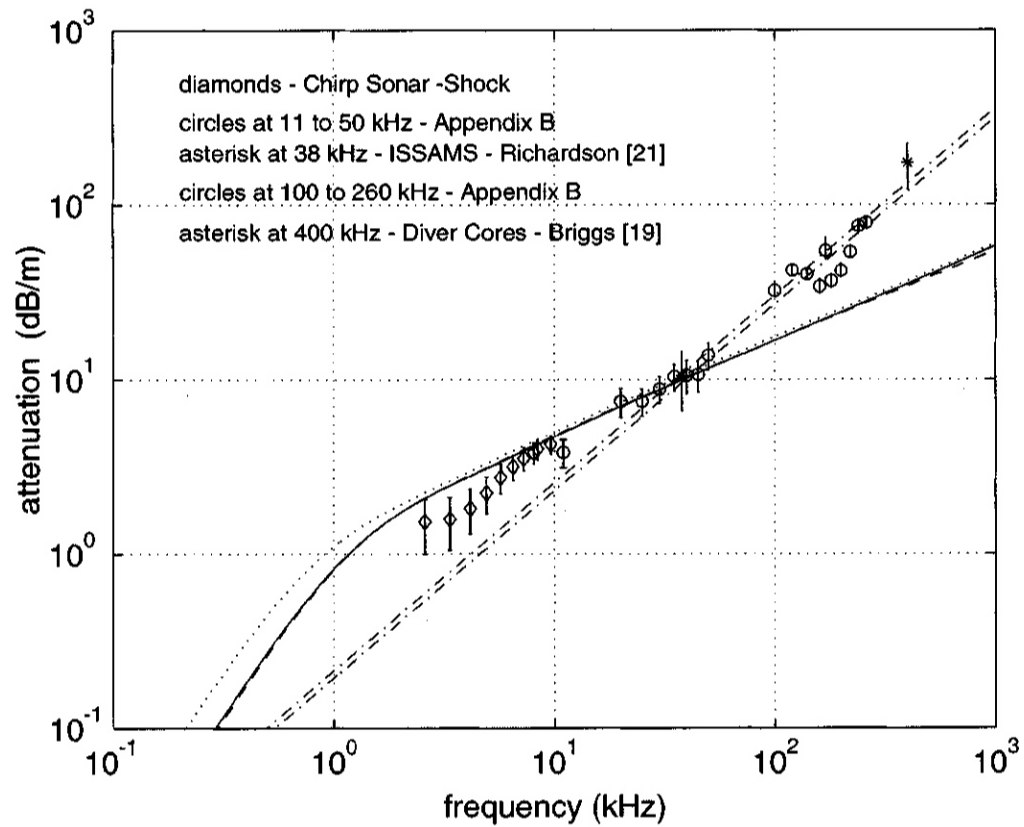


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [27].) Also note that there is attenuation data below about 3 kHz.

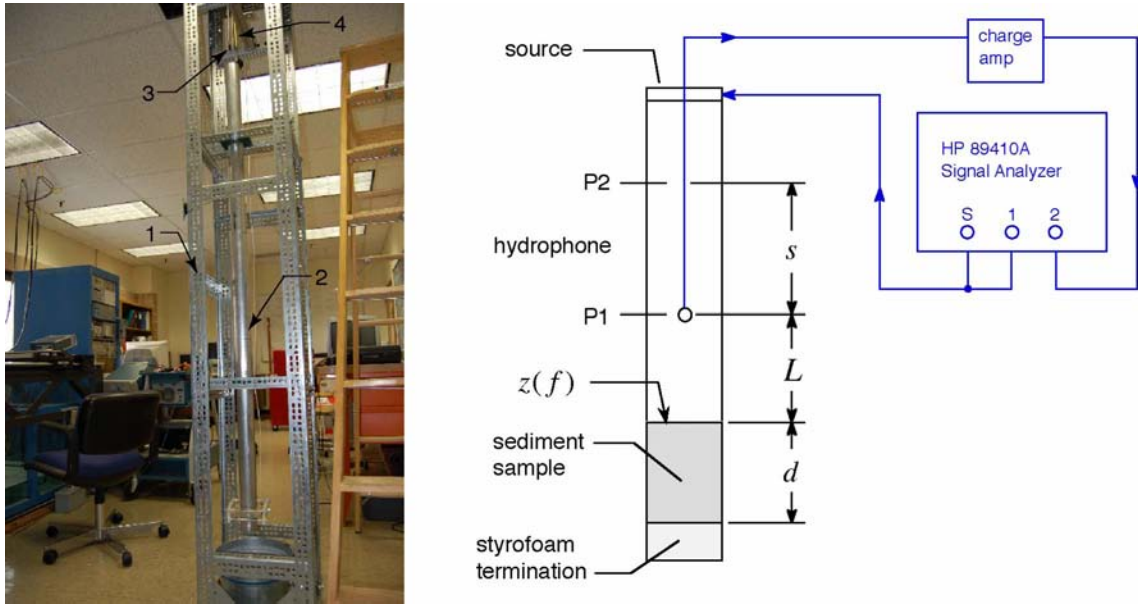


Fig. 2. The photograph on the left documents the state of the impedance tube system at the beginning of this fiscal year. Some key components: the supporting framework (1), the impedance tube (2), the hydrophone (3), and the hydrophone positioning system (4). On the right is a schematic diagram of the impedance tube system.

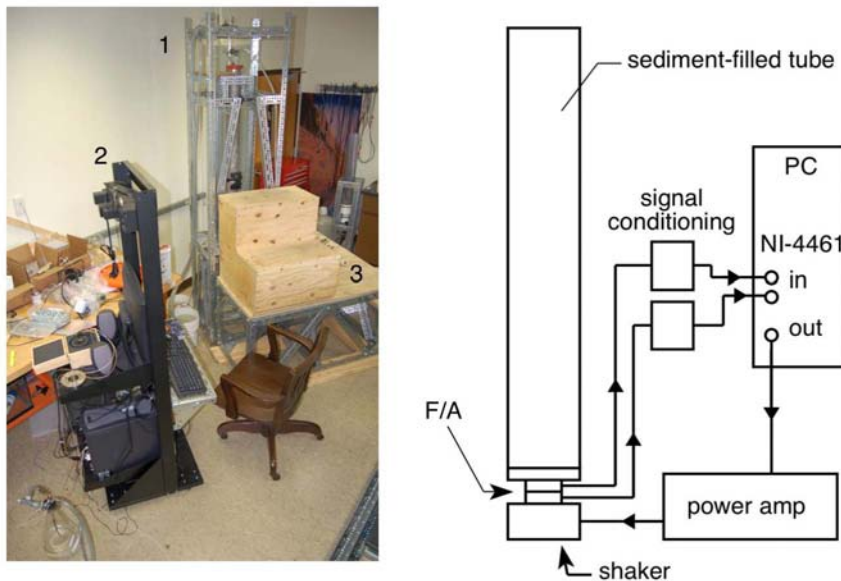


Fig. 3. On the left is shown a photograph of the impedance tube facility with components: the support frame and tube (1), the computer and data acquisition system (2), and the scaffolding (3). On the right, the view down the center of the tube is shown, illuminated from the far end with a flashlight, after gun drilling and honing. Note the smoothness of the inner tube wall.

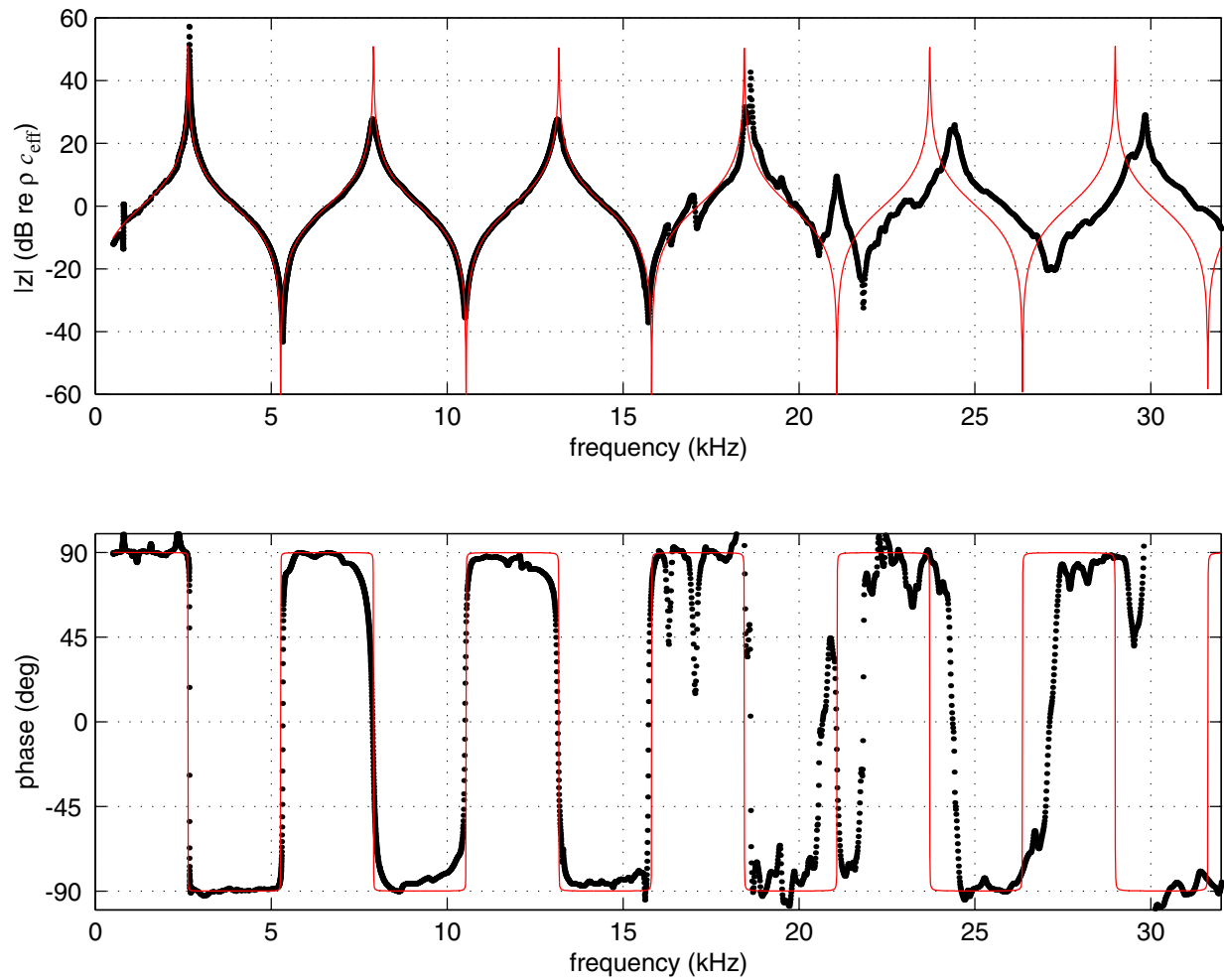


Fig. 4. The magnitude and phase of the measured impedance of the water-filled sample holder terminated with styrofoam is plotted with black dots. Above 15 kHz, the plane wave assumption required for the impedance measurement is of diminishing validity, resulting in erroneous results. The predicted impedance is plotted with the solid red line.

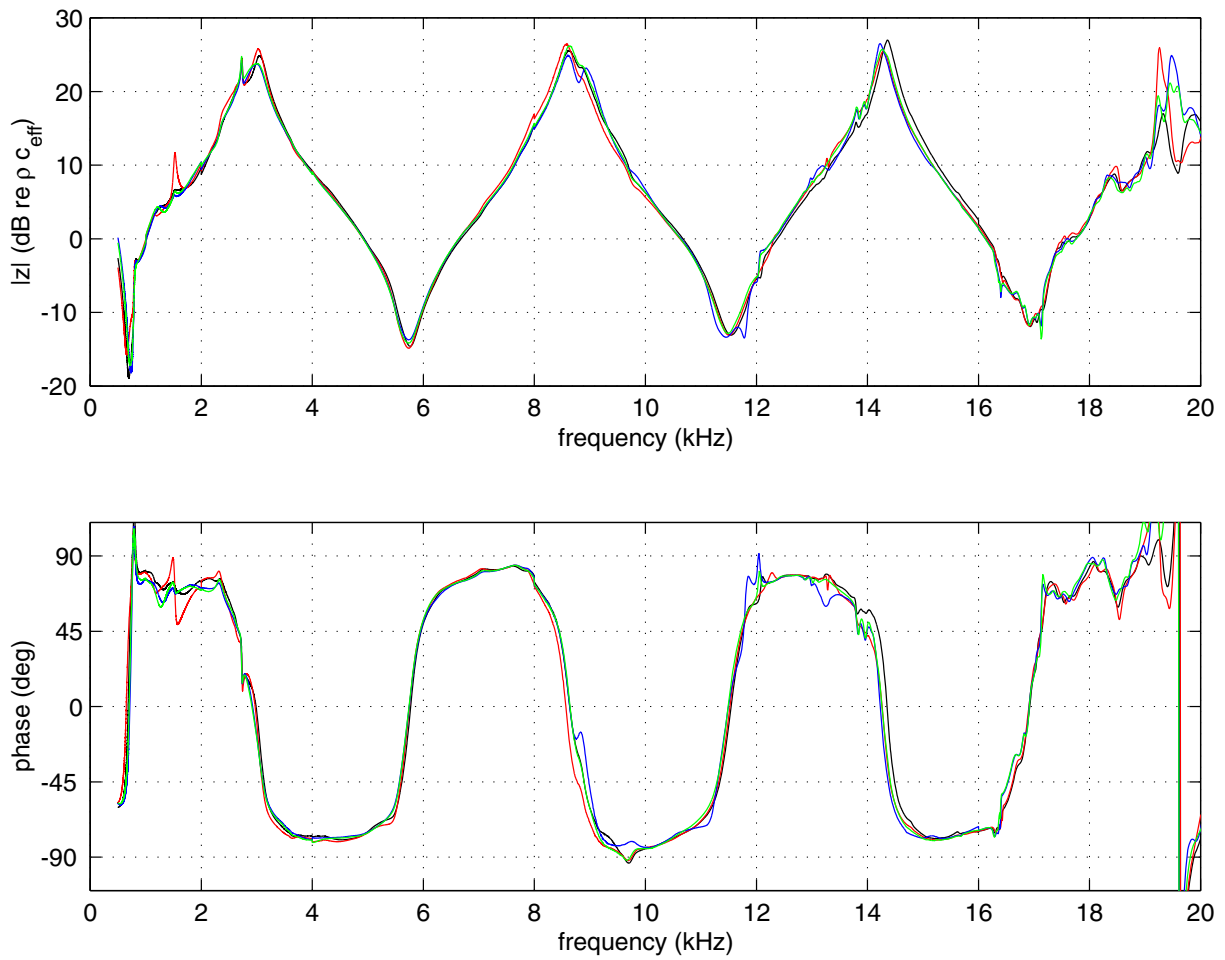


Fig. 5. Measured impedance of unwashed/unsieved and washed/sieved reconstituted sand sediment samples plotted together for comparison. The red and black curves are for the unwashed case and the blue and green curves are for the washed case. Little significant difference is seen. Note that the frequency scale is different than that in Fig. 4.

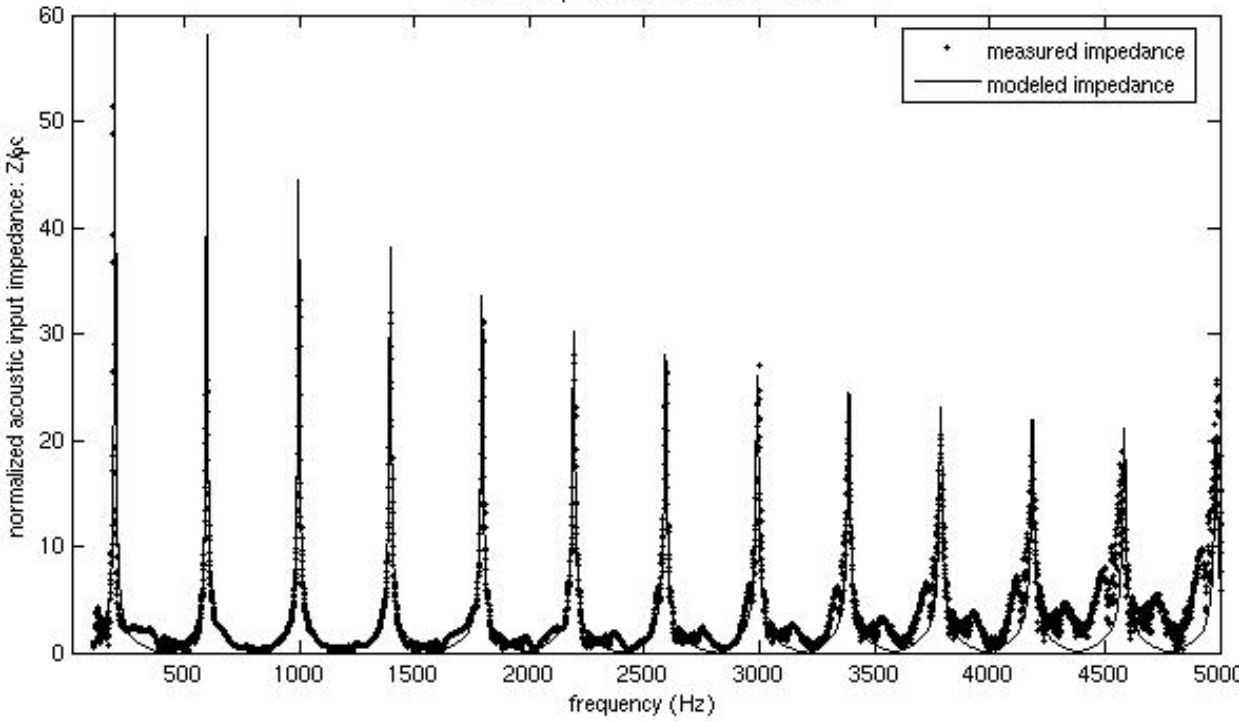


Fig. 6. Impedance of a 1.8 meter long column of water measured using the Mert method [17]. The solid line is the predicted impedance using tabulated values of water density and temperature-dependent sound speed. The dots are the measurement data. Good agreement is seen between predicted and measured values. This indicates that the new Mert method is accurate and it will be beneficial because it will allow us to reach down to lower frequencies.

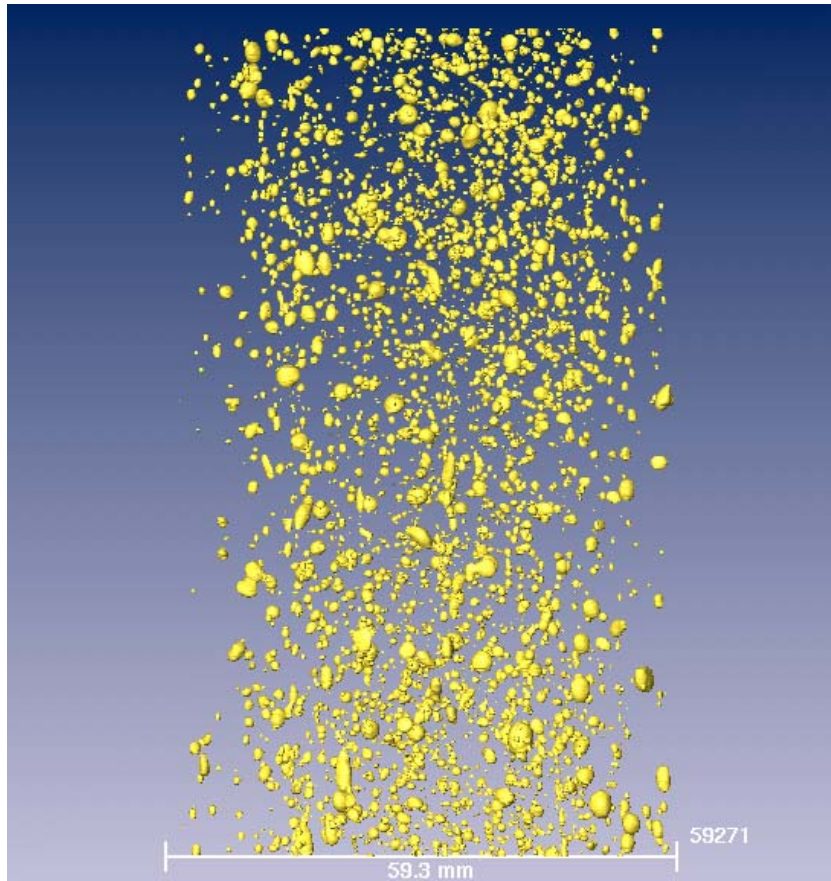


Fig. 7. A single image from the computed x-ray tomography scan of the Kaolinite sediment sample contained with the 1-D acoustic resonator. The yellow blobs are air bubbles.

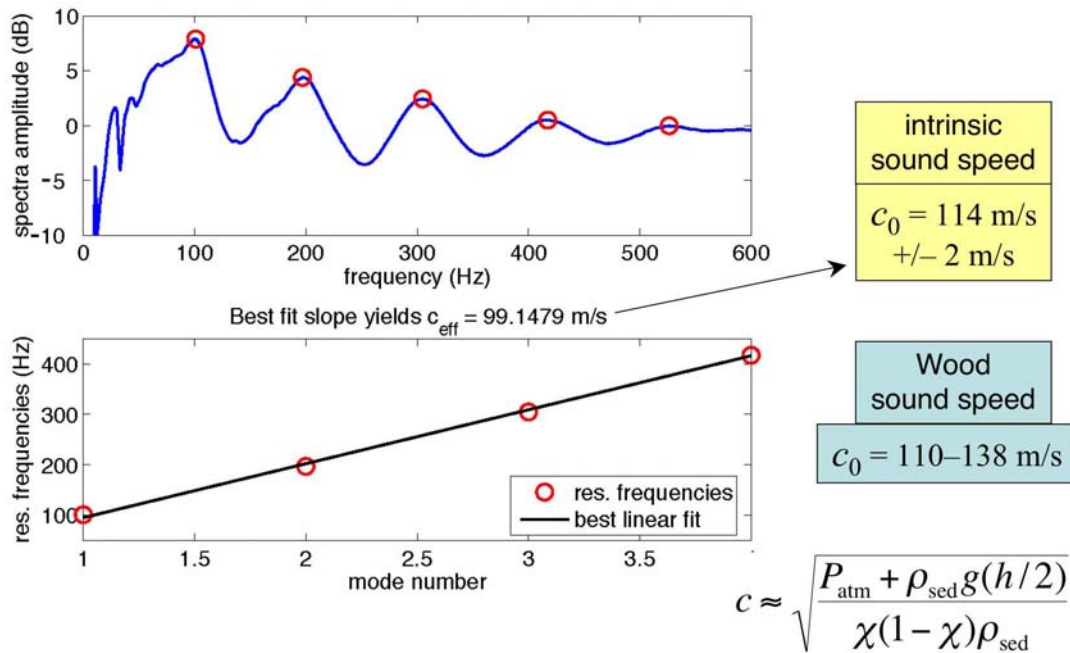


Fig. 8. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with reconstituted bubbly Kaolinite sediment. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from the imaging analysis, as discussed in Fig. 7. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm} , the acceleration due to gravity g , and the sediment column height h . The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters.

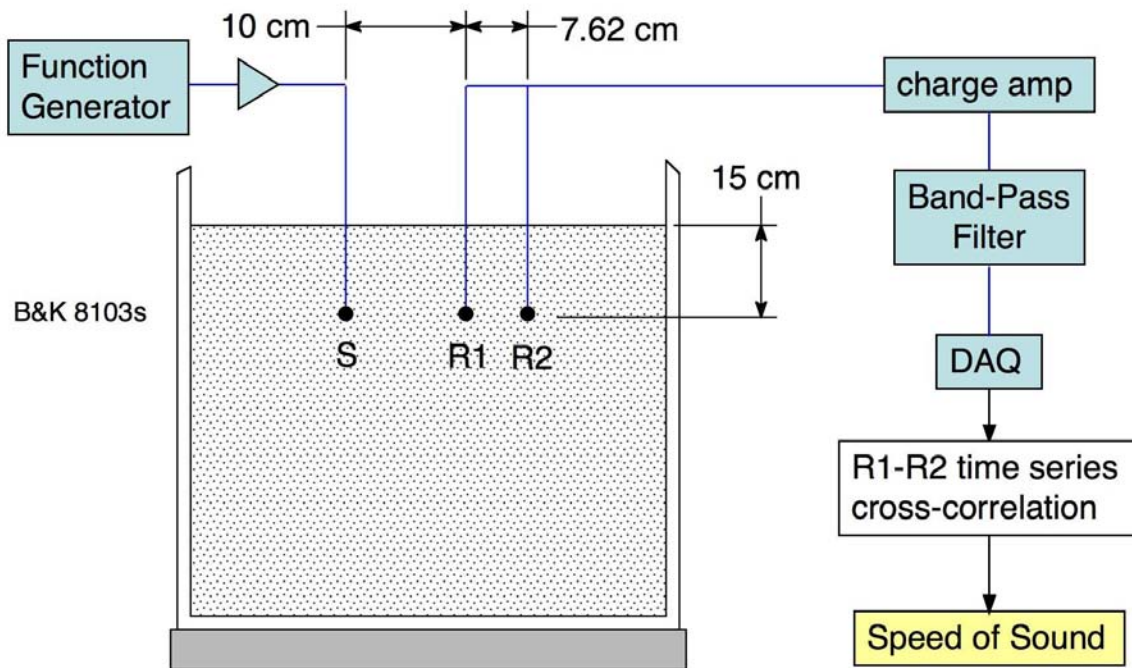


Fig. 9. A schematic diagram of the time-of-flight experiment is shown. A large thin-walled cylindrical container was filled with 60°C degassed water and sorted and washed medium grain blasting sand. Three B&K 8103 hydrophones were placed in the sediment and time-of-flight measurements were obtained after cooling. A function generator and power amplifier were used to drive one of the 8103s as a source. The remaining two 8103s were used as receivers. Their signals were conditioned with a charge amp and a band-pass filter. The voltage signals were acquired with a digital oscilloscope and cross correlated to extract the time-of-flight. Sound speed was then calculated from the 7.62 cm sensor separation distance.

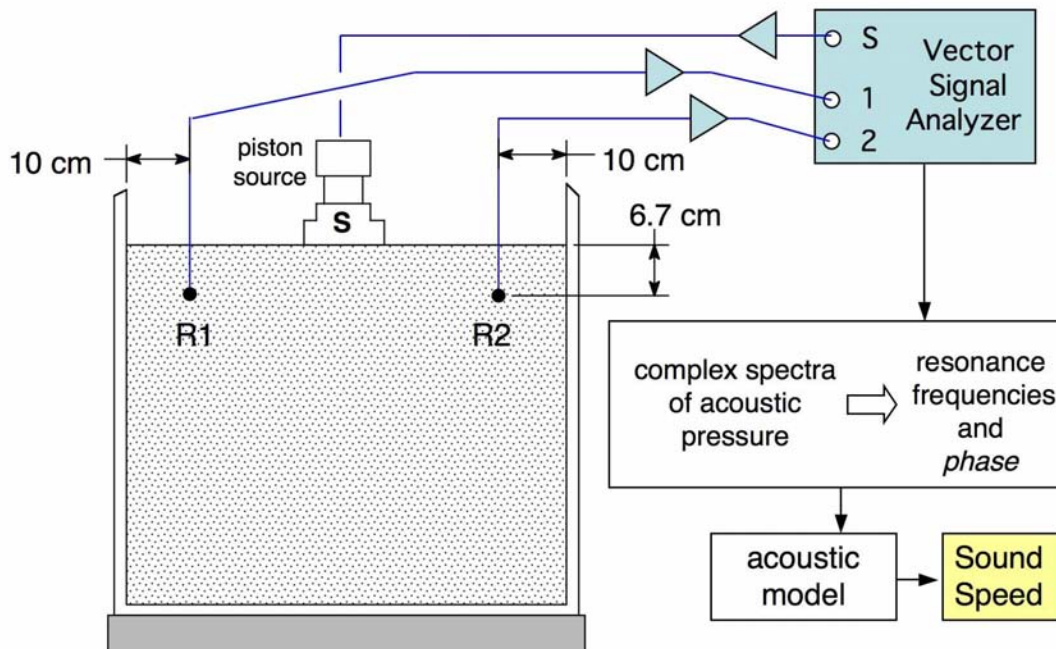


Fig. 10. A schematic diagram of the resonance experiment is shown. A constant-velocity tonpiltz source was used to excite the system. By placing it in the center, symmetric modes were excited. By placing the source midway between the center and the wall, asymmetric modes were excited. The source was driven with periodic chirps and the pressure spectra were recorded at positions R1 and R2. Analysis of the spectra yielded resonance frequencies which were in turn related to the frequency-dependent sound speed of the sediment. The effect of the finite impedance of the tank walls was accounted for, and found to be small.

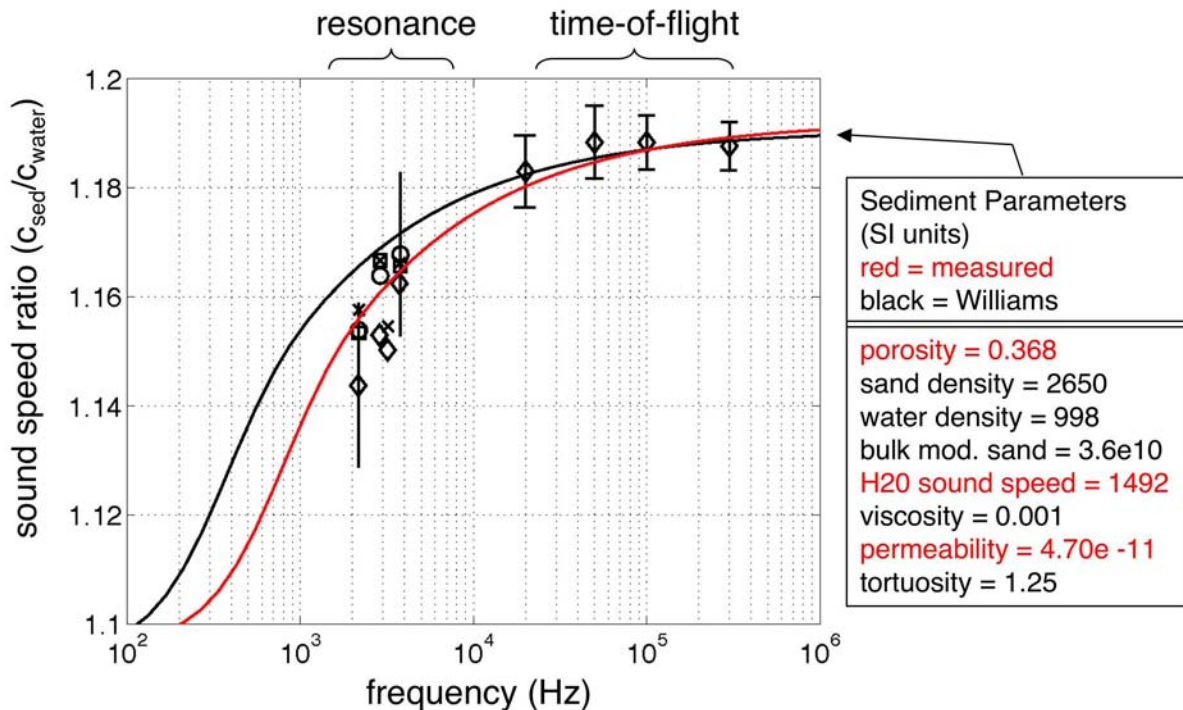


Fig. 11. Normalized sound speed measurements are compared to the EDFM (solid lines). The red curve corresponds to the EDFM prediction using the new permeability and porosity measurements. The black curve is from the previous analysis, in which we did not have a measurement of permeability, but used a canonical value from the literature. Error bars represent length and time uncertainties, but due to the close grouping of some of the data, they are not shown for every data point. The material parameters (in pure SI units) used for evaluation of the red EDFM curve are shown in the table to the right of the plot. The values shown in red were measured and specifically refer to the sediment in this study. The values shown in black were taken from Ref. [10], for a similar type of sand. No adjustment of material parameters was conducted, nor was any fitting performed. The EDFM agrees very well with the time-of-flight measurements, within the range of measurement uncertainty in each case. All of the resonance-based measurements are now in agreement with the EDFM, within the range of measurement uncertainty. One can now conclude that the EDFM accurately predicts the sound speeds in this well-degassed water-saturated sand sediment.

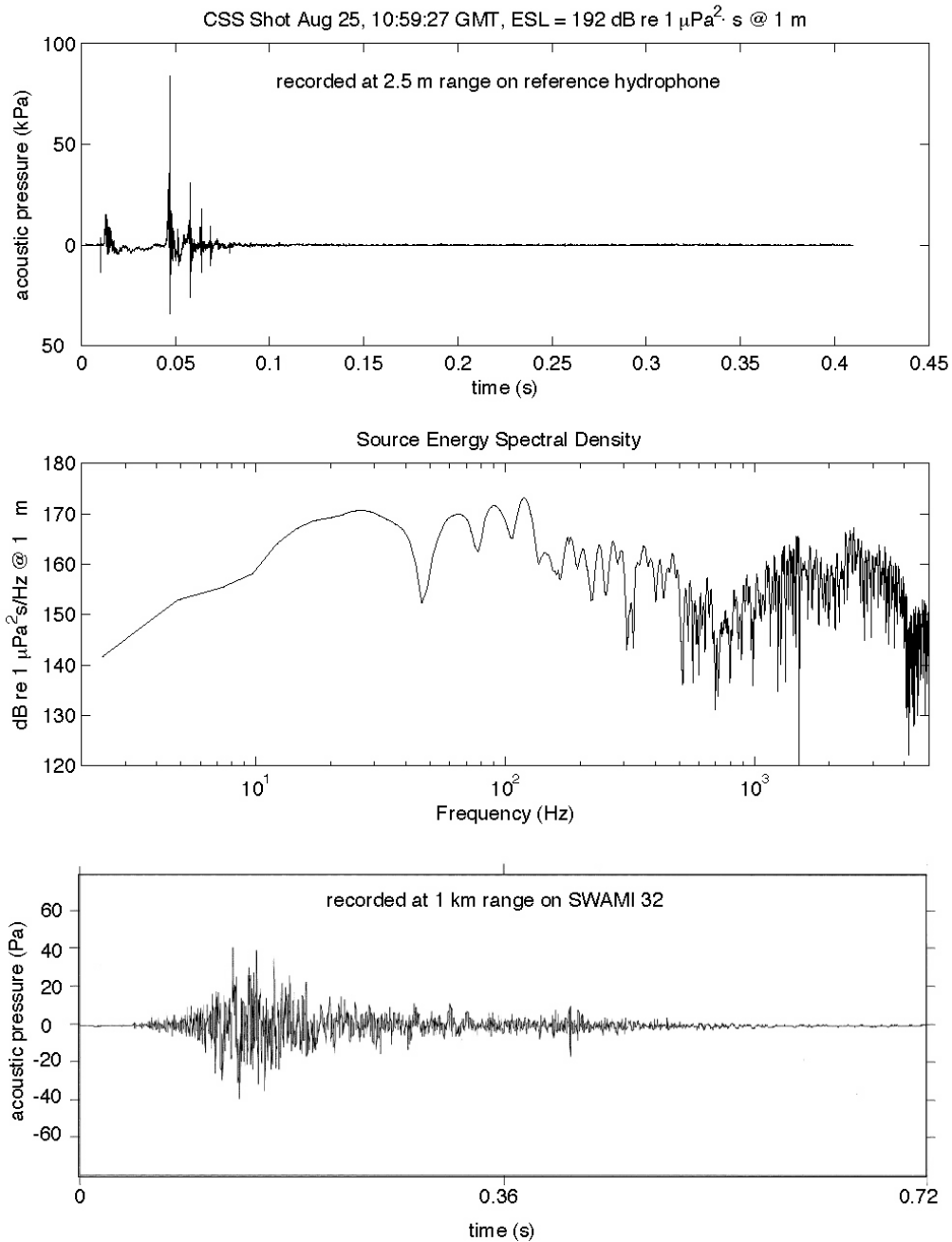


Fig. 12. CSS shot from SW06. The top curve was recorded on a reference hydrophone at a range of 2.5 m. The middle curve is the Source Energy Spectral Density of the shot in the top frame. The bottom curve is the shot recorded at a range of 1 km on SWAMI 32.