

Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

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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 [1] and acoustic resonator tube [2, 3] methods, in the frequency range of approximately 300 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. These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [4-11] 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 [12] 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 has been to investigate other ocean-bottom materials of opportunity utilizing the techniques and measurement instrumentation developed for this work. To date these materials have been gas-bearing sediments and seagrasses. Finally, the author participated in SW06 and therefore a tertiary objective this FY was to participate in the analysis of some of the SW06 data in collaboration with other ONR PIs.

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APPROACH

The impedance tube technique has been adopted as a standard technique [13-15] 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. [16] 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. [17] 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 operates in the frequency range in which dispersion is expected (about 300 Hz to 30 kHz) in typical sandy sediments. It has been used to make measurements, which are presented below, but we are continuing to refine the technique and instrumentation. Two impedance measurement techniques can be utilized with the apparatus, [18, 19] which do not require movement of the sensors, and minimize errors due to sensor position uncertainty. The apparatus is also being used with the resonator method [2, 3] of measuring material properties. Finally, we have incorporated 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 is based on and extended from existing work for lossy fluid coupling in elastic waveguides, [19, 20] additional sample-wall boundary effects, [21] sample-fluid boundary effects [22] and asymmetric excitation. [23] The instrument is being used in the laboratory to investigate artificial and natural sediments *in vitro*. A technique was adopted this year that allowed for the control of porosity, [24] and has been applied to new high frequency (above 50 kHz) measurement, presented below.

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. Ryan L. Renfrow, a UTME senior and an Undergraduate Research Assistant on the project, serves as an electromechanical technician and provided machine shop, procurement and software support. Theodore F. Argo IV is a UTME Ph.D. student who contributes to all aspects of the project.

WORK COMPLETED

Primary Objective—Laboratory Sediment Investigation: The difficulties discussed last year using the low frequency measurement methods outlined in Fig. 2, and illustrated in Fig. 3, have been successfully attributed to the Janssen effect, [25] which will apply to any vertical impedance or resonator tube technique in which the column becomes too long, relative to a length scale of structure created by the sediment grains distributing the overburden load to the walls in force chains. The result is that the material exhibits a highly inhomogeneous stiffness that significantly differs from that seen in the unconfined material, and hence appears to significantly alter wave propagation. A visualization of this is shown in Fig. 4. [26] To overcome this problem, the new long resonator tube which was

formerly deployed in a vertical orientation, has now been deployed horizontally. Significant engineering effort has been expended to reorient the experimental apparatus and the associated sample handling system. New measurements of low frequency sound speed and attenuation are expected from this system in the near future.

We began a collaboration with a research group in the University of Texas at Austin's physics department that studies the dynamics of granular material and also with a group at The Max Planck Institute for Dynamics and Self-Organization (Göttingen, Germany). We adapted a technique they jointly developed [24] to create samples of water-saturated granular materials with variable porosity using a fluidization technique. We have conducted a series of sound speed and attenuation measurements at high frequencies (100–750 kHz) in glass-bead sediments with a porosity range from 0.38 to 0.44 and compared them to the predictions of the Biot-Stoll model. [10]

Secondary Objectives—Gas-bearing Sediments: We continued our collaboration with the Seafloor Sciences Group at NRL-SSC on the acoustics of 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 at NRL-SSC in January 2006. Our 1-D acoustic resonator technique [2] was used to measure the sound speed inside the sediment samples. A high frequency (400 kHz) time-of-flight technique (using the Kevin Briggs ear-muffs apparatus [27]) was also used to measure the sound speed. The imaging scans yielded the bubble size distribution and the total void fraction (gas content) of the sediment. A model was developed this year to describe the low frequency sound speed in shallow, fluid-like gas bearing sediments, based on a simplified Wood's equation, and it was found to agree with measurements in a sediment of kaolinite, distilled water and gas bubbles, which resulted in a new publication. [28]

Secondary Objectives—Seagrass Acoustics: Our previous collaboration with the seagrass biologist, Dr. Kenneth Dunton, of the University of Texas Marine Science Institute on the acoustics of sediments containing seagrasses has continued. Our acoustic resonator technique was used to make additional measurements of the effective low frequency acoustic properties of three gulf-coast species, *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). Additional measurements and analysis were conducted this fiscal year which resulted in a manuscript which is currently accepted for publication pending revision. [29]

Tertiary Objective—SW06 Data Analysis: The combusive sound source (CSS) was deployed by this author and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon last year's analysis and has further shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions. Geoacoustic inversion using CSS signals has been optimized, resulting in a publication [30] and further analysis of the frequency dependency of a sandy bottom on the New Jersey shelf has resulted in a new publication. [31]

RESULTS

Primary Objective—Laboratory Sediment Investigation: The fluidized bed apparatus that was designed and constructed to measure the sound speed and attenuation in water-saturated sediments as a function of frequency and porosity is shown in Fig. 5. Water is pumped up through the bead sample, which fluidizes the sediment. The height of the sediment column increases in proportion to the flow rate. When the flow is terminated, the sample settles back to an equilibrium porosity that is higher than the original randomly packed porosity. The resulting equilibrium porosity is a function of the

flow rate and flow rate history in a known way, hence one can prepare a sediment of a particular porosity. High frequency measurements of the speed of sound in water-saturated glass bead sediments (bead radius = 250 μm) are presented and compared to the Biot-Stoll model [10] in Fig. 6 for three porosities. These are preliminary results and additional analysis is required to fully understand the dispersion seen in this data. It is clear that the Biot-Stoll model correctly predicts the effect of porosity.

Secondary Objectives—Gas-bearing Sediments: The collaborative work with NRL-SSC resulted in the measurement of sound speed of a reconstituted gas-bearing kaolinite sediment and a natural mud from Bay St. Louis, MS. Contemporaneous measurements of the bubble size distribution were also obtained. Further analysis of this data set was conducted in the current fiscal year and the results were published. [28] A single image from the tomography scan is shown in Fig. 7. From this data, the overall sample void fraction was found. 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. Note that these results indicate that the only bulk sediment property required for the prediction of sound speed in shallow, fluid-like gas bearing sediments is the bulk sediment density and the total gas volume fraction. None of the other typical Biot sediment parameters are needed, nor is the bubble size distribution needed. Also note that the traditional high frequency time-of-flight measurement technique failed in the gassy kaolinite due to excessive attenuation.

Secondary Objectives—Seagrass Acoustics: Additional experiments were conducted using the resonator technique to assess the hypothesis that seagrass is acoustically dominated by its gas content, and that Wood's equation could be used to model sound propagation in seagrass beds as an effective medium. A typical result for the species *Thalassia testudinum* (turtle grass) is shown in Fig. 9. The two curves show plant volume fraction $V_{\text{leaves}}/V_{\text{tot}}$ (measured by acoustic and image-based techniques) as a function of the number of leaves placed inside the resonator. The black curve yields an acoustically-determined plant internal void fraction $\chi_{\text{leaf, a}} = 0.034$, via best fit of the equation at the top of the figure. The actual plant internal void fraction, determined using microscopic cross-section image analysis (Fig. 10), was found to be $\chi_{\text{leaf}} = 0.23$. Similar results were found the *Thalassia testudinum* (turtle grass) rhizomes (underground root structures) and the leaves and rhizomes of the other two species tested, *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). The above hypothesis is refuted and indicates that forward models of sound propagation and scattering in seagrass beds will require not only knowledge of the gas content, but knowledge of the plant tissue properties and structures, too.

A comparison of the ratio of the image-based to acoustically determined void fractions for both leaves and rhizomes of all three species reveal some interesting differences (Fig. 11) that reflect the acoustic importance of the tissue. A ratio of unity indicates plants that behave acoustically like air bubbles in water. An increasing ratio indicates increasing tissue stiffness, which effectively reduces the acoustic contrast of the internal gas and thereby reduces the acoustic contrast of the plant. For all three species, the rhizome tissue is stiffer than the leaf tissue, and there is a large difference between the two tissues for both *Thalassia* and *Halodule*. *Syringodium* exhibits the highest tissue stiffness of the three species, and the leaf and tissue stiffness is of similar magnitude. The high stiffness of *Syringodium* leaves may

be explained by the cylindrical shape of its above-ground photosynthetic tissues. Volumetric excitation of the pore space places the circumferential tissue in tension, with hoop-like structures resisting expansion. For all three species, the rhizomes are circular in cross section with internal gas-filled pores, similar to *Syringodium* leaves. In contrast, the leaves of *Thalassia* and *Halodule* are flat and there is little tissue to resist the expansion. These results have been accepted for publication pending a minor revision. [29]

Tertiary Objective—Sediment Attenuation in SW06: The frequency dependency of a sandy sediment sound speed along a track in SW06 was analyzed [31] and found to exhibit low frequency attenuation in good agreement with predictions of the Biot-Stoll model. [10] The results are shown in Fig. 12, and the new low frequency attenuation values show a slope proportional to the frequency squared.

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 new laboratory results reported here indicate that the Biot-Stoll model [10] correctly predicts the porosity dependency of high frequency sound speed in water saturated sand. Low frequency (53–2000 Hz) attenuation data from SW06 are also well described by Biot-Stoll and clearly follow the low frequency limiting slope of frequency squared. We are continuing our efforts to get ever-lower- frequency and more accurate laboratory measurements with and increased understanding of the measurement uncertainties.

Fluid-like shallow gas-bearing sediments were shown to have acoustic properties that depend only on the sediment bulk density and the void fraction as given by a simplified version of Wood's Equation. Two types of tissue from three different species of seagrass were shown to depend on tissue acoustic properties in addition to the gas content, and hence were not described by Wood's equation.

As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems and environmental surveys. 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 is proving to be a useful tool for ocean acoustics experiments.

TRANSITIONS

This PI received \$275k in the current fiscal from the Naval Oceanographic Office for further development of the combustive sound source (CSS) as a replacement for explosives in ocean surveys.

This PI received \$249k from the ONR Code 332 to perform laboratory measurements of the sound speed in methane hydrates, using the resonator method developed with the present grant.

This PI will be starting a project in 2009, funded by Shell Oil, to use bubbles to reduce the radiated noise from offshore drilling operations. Much of this PI's experience with bubbles was due to a project previously funded by ONR and also due to the current grant.

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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FIGURES

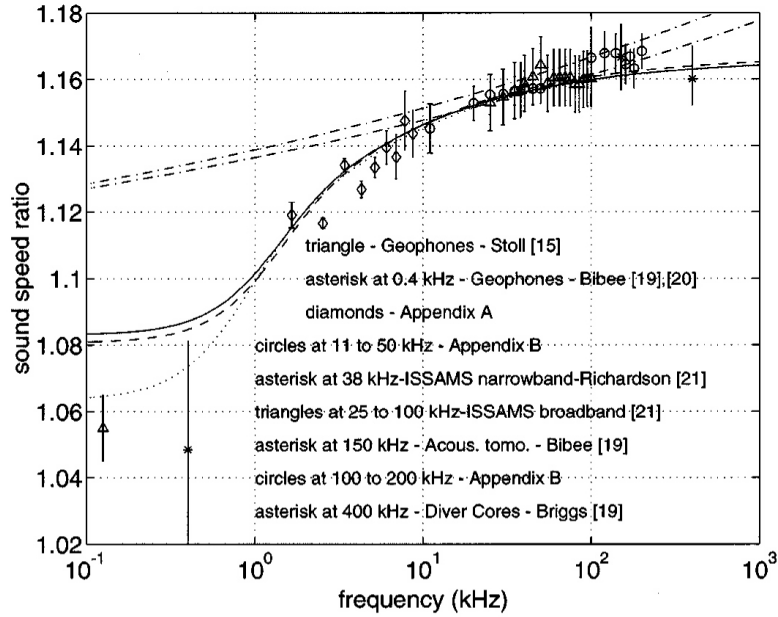


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [32].
The theoretical curves are: solid line=Biot/Stoll [10]; dashed line=Williams [11], dash-dot lines=Buckingham's model for two values of fluid viscosity [9]; 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 [32].)

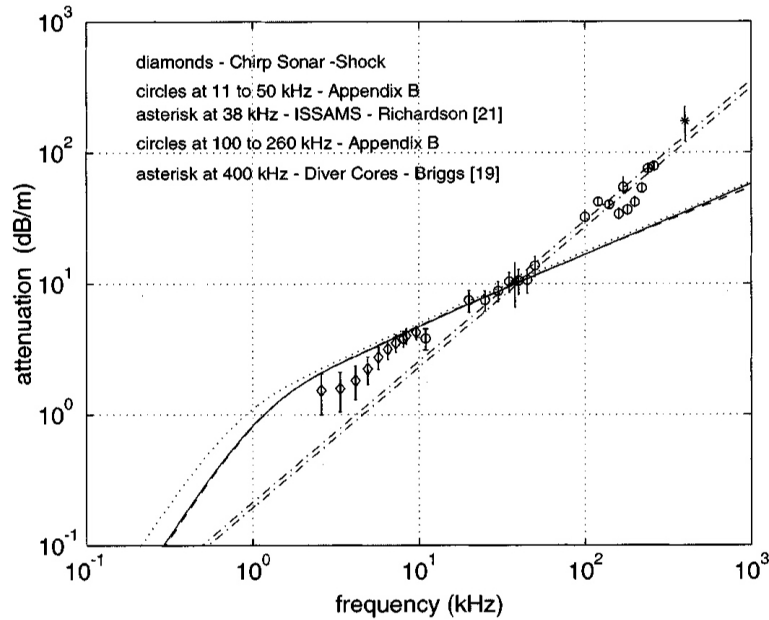


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [32].)
Also note that there is attenuation data below about 3 kHz.

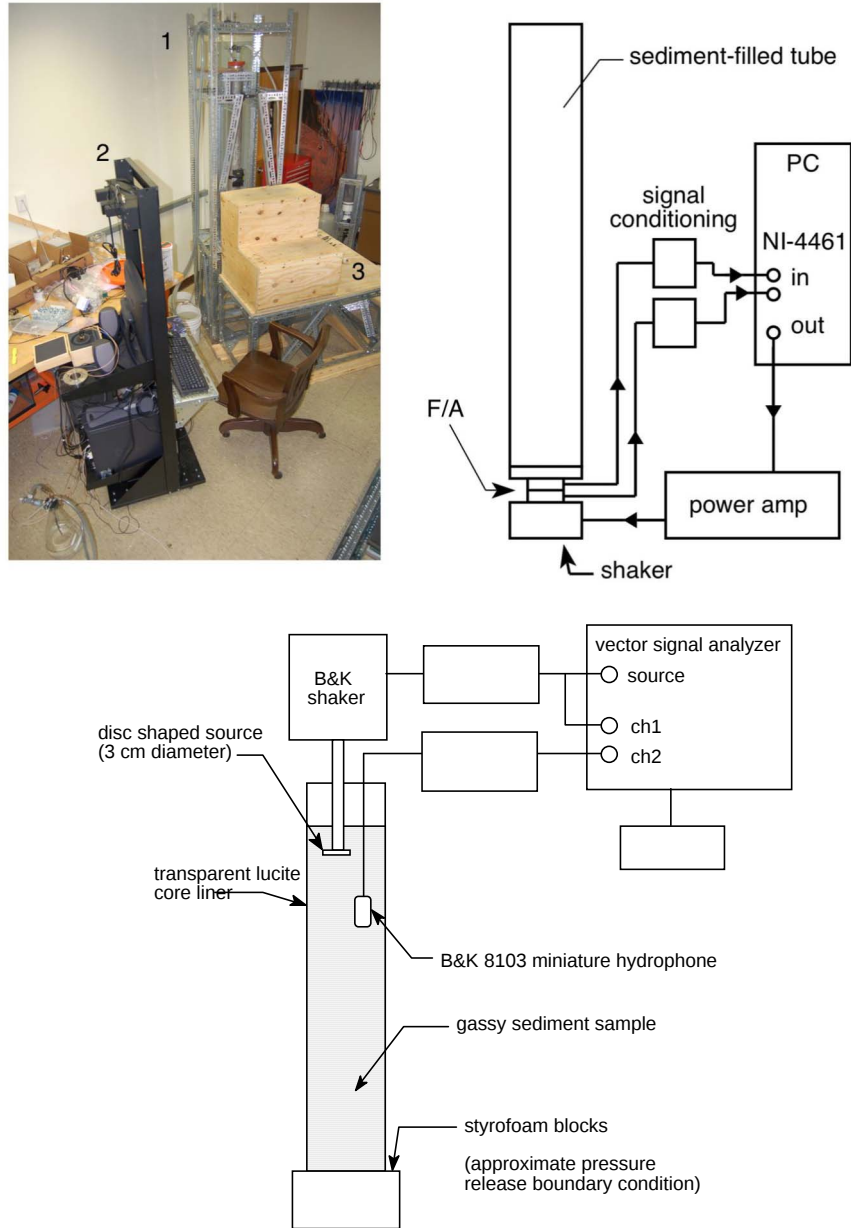


Fig. 2. The upper left is a photograph of the impedance tube facility: the support frame and tube (1), the computer and data acquisition system (2), and the scaffolding (3). On the upper right, the schematic of the Mert apparatus [19] is shown. In the lower frame, a schematic of the resonator method is shown.

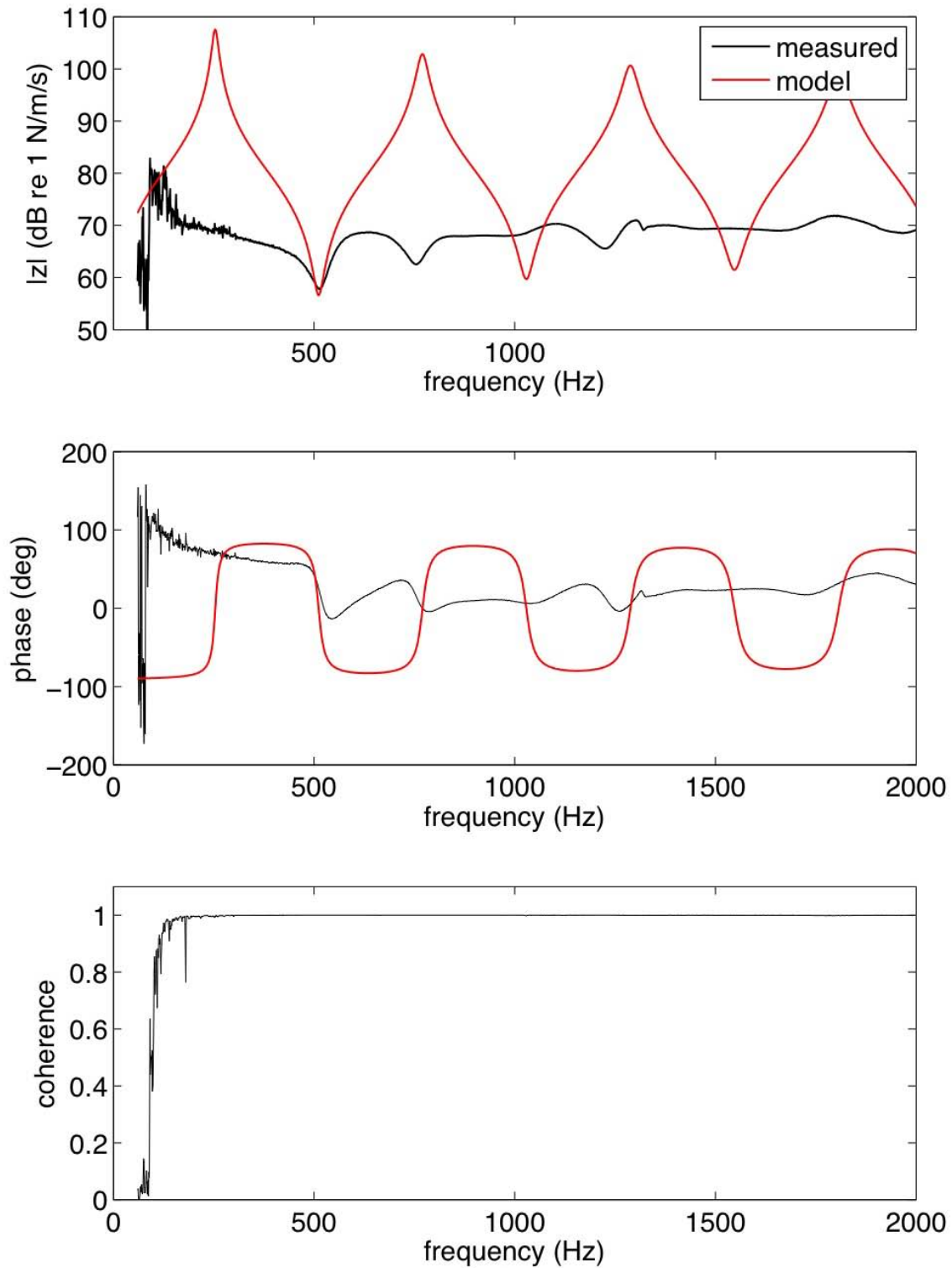


Fig. 3. The long (min frequency = 200 Hz) impedance tube developed last fiscal year was used to obtain the data shown here. The material that filled the tube was a reconstituted water-saturated sand sediment. The magnitude of the impedance is shown in the upper plot. The phase and coherence are shown in the lower two plots. The predicted characteristic acoustic resonances (minima of the upper red curve) are absent from the measured data (black curve).

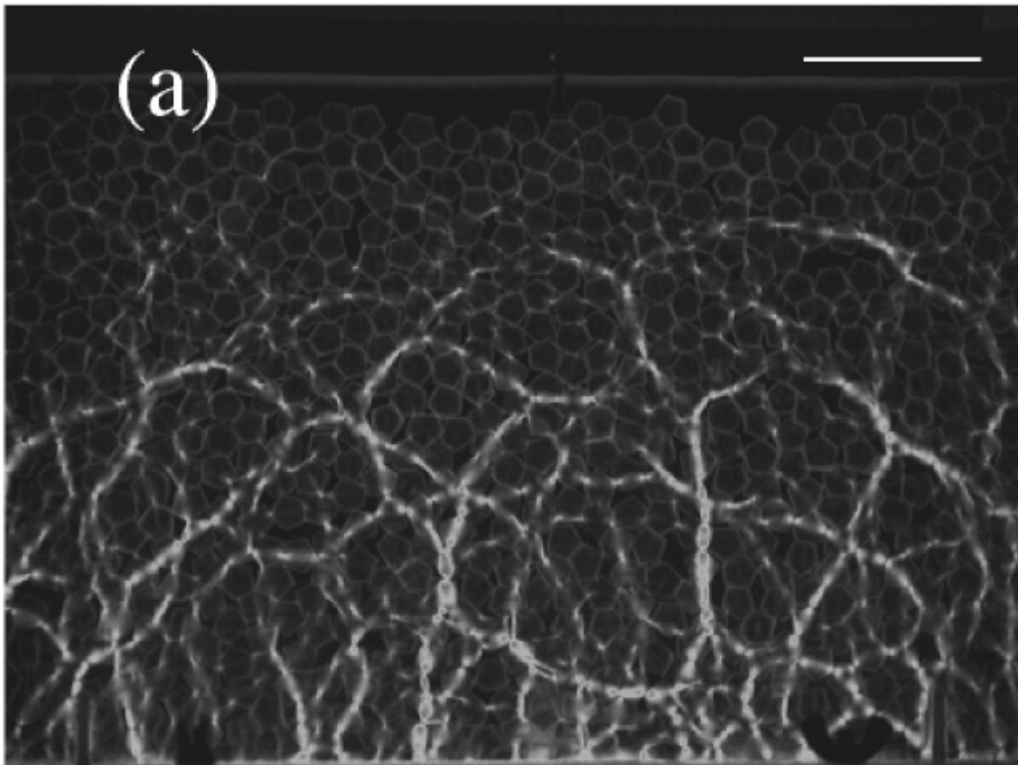


Fig. 4. A two-dimensional packing of photoelastic pentagonal beads is shown under hydrostatic load. [26] The beads under stress appear lighter in comparison to beads not under stress. Hence force chains are seen carrying the load in an inhomogeneous pattern. The white vertical bar is 5 cm.

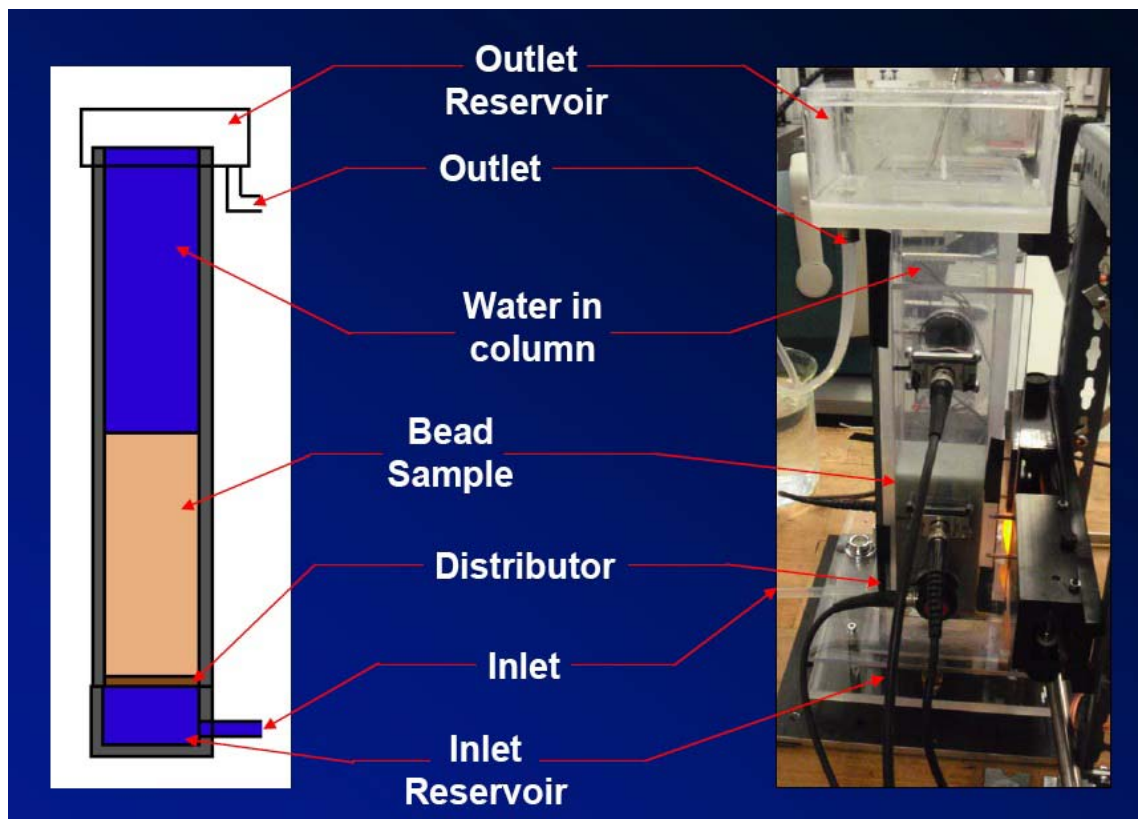


Fig. 5. *The fluidized bed and high frequency time-of-flight measurement apparatus is shown in schematic on the left, and in a photo on the right. The BNC cables on the near face of the apparatus are the acoustic transducers.*

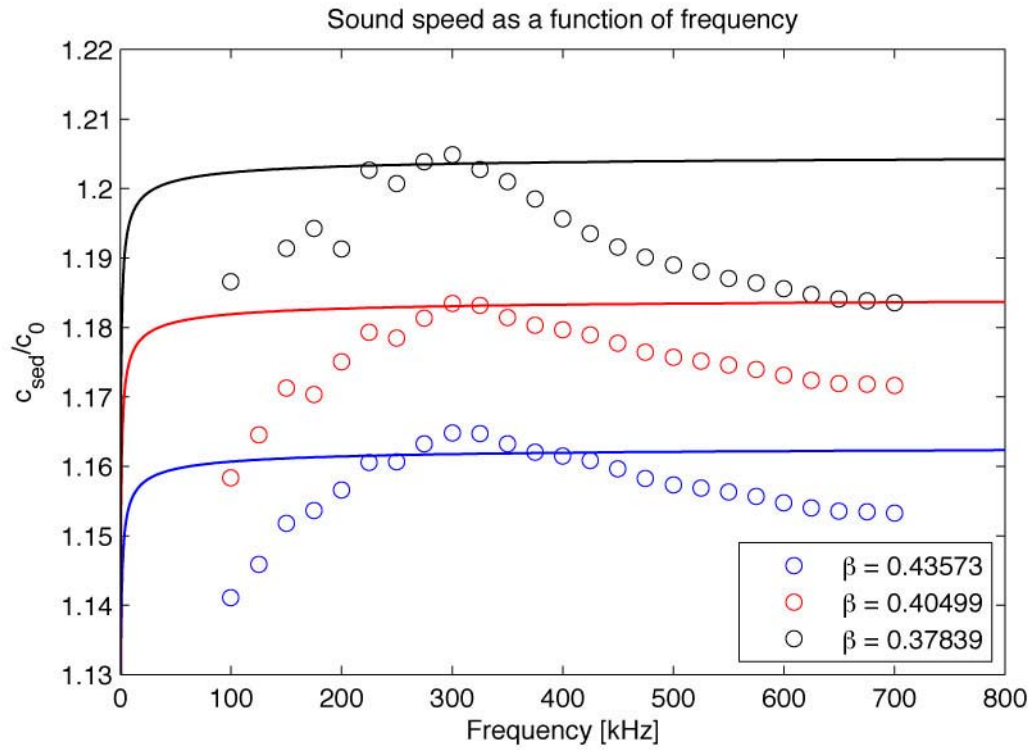


Fig. 6. High frequency time-of-flight measurements of the sound speed in water-saturated glass bead sediments are presented as a function of frequency for three porosities. The sound speed is observed to rise with positive dispersion through 300 kHz and then negative dispersion is observed. The solid lines represent predictions of the Biot-Stoll model. [10]

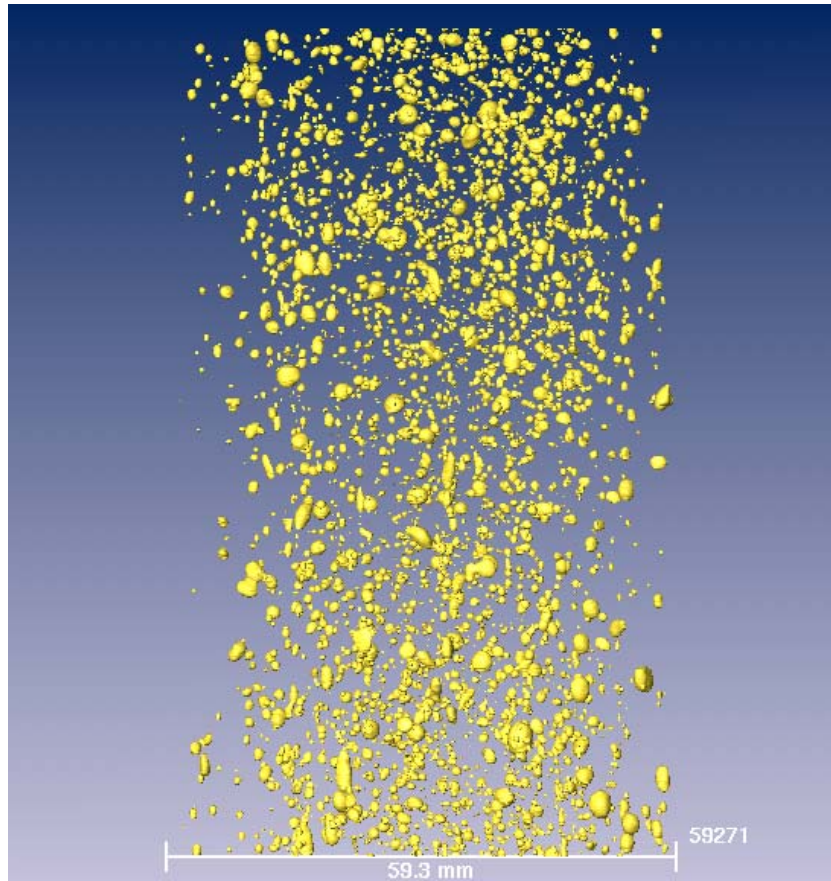


Fig. 7. A single image from the computed x-ray tomography scan of the kaolinite sediment sample contained within the 1-D acoustic resonator. The yellow blobs are air bubbles. The data was manipulated to give the volume of each bubble, and the total void fraction and the effective spherical bubble size distribution were determined.

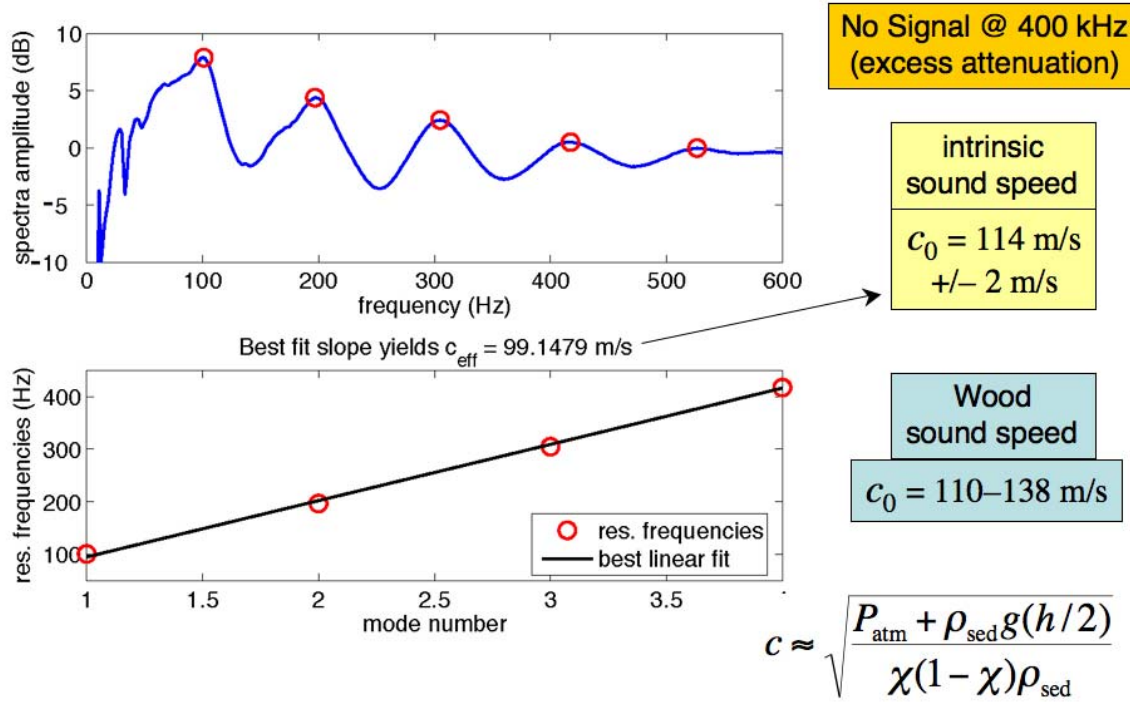


Fig. 8. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with reconstituted bubbly kaolinite sediment. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. A simplified version of Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from the image analysis, as discussed in Fig. 9. 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. The simplified Wood's equation accurately describes the measured sound speed. In the orange box on the upper right, the high frequency time-of-flight measurement is shown, which in this case yielded no result.

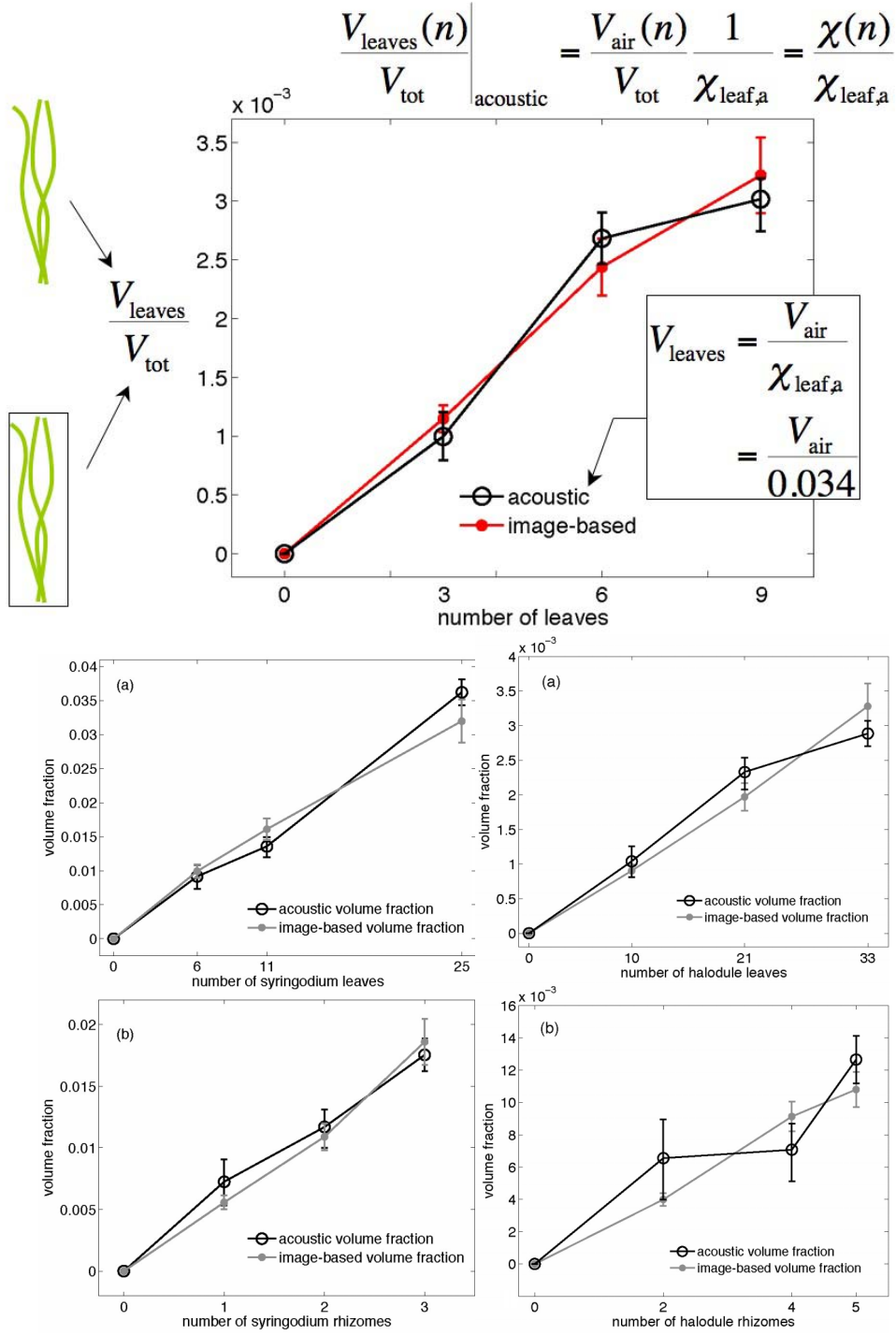


Fig. 9. In the top frame, the apparent acoustic volume fraction of *Thalassia* leaves is compared to the volume fraction obtained by image analysis of the leaf physical volume. The black curve yields an internal leaf void fraction of 0.034. The same type of measurement results and analysis is presented for two additional species, *Syringodium* and *Halodule*, for both leaves and rhizomes (root tissue). All these results are assimilated in Fig. 11.

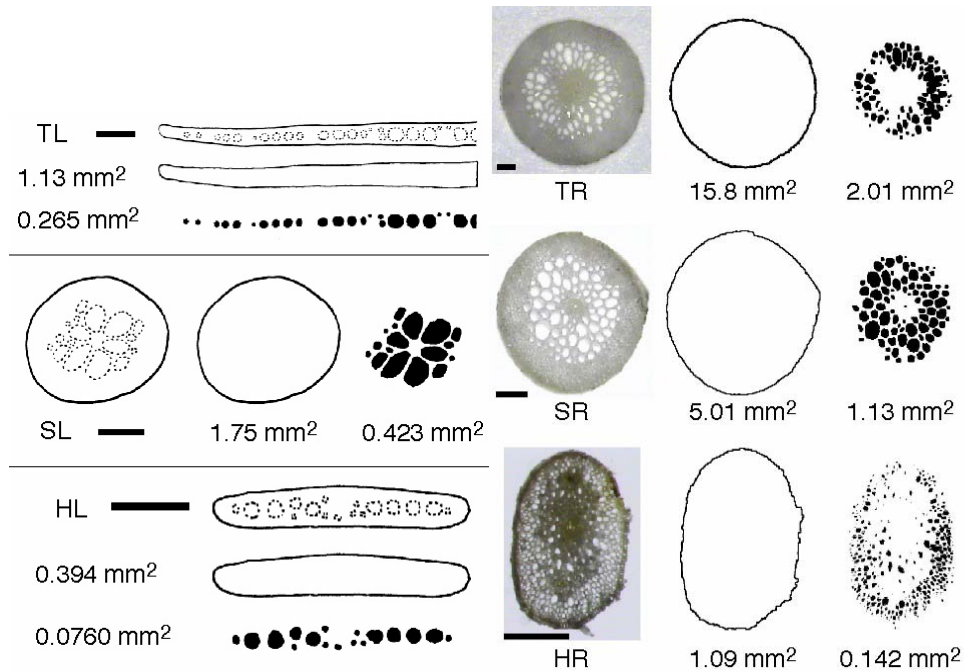


Fig. 10. Left column: Microscopic cross sections of seagrass leaves (L) for *Thalassia* (T; top panel), *Syringodium* (S; middle panel) and *Halodule* (H; bottom panel). Since the cross-sections are nearly uniform perpendicular to the plane of the image, the void fraction is pore area/total area. The aerenchyma are the circular features outlined with dashed lines or with black fill. Horizontal black scale bars are 0.5 mm in length. In each panel, the total leaf and pore area are shown adjacent to their corresponding images. Right column: Microscopic cross sections of seagrass rhizomes (R) for the three seagrass species. Abbreviations and notes as in left column.

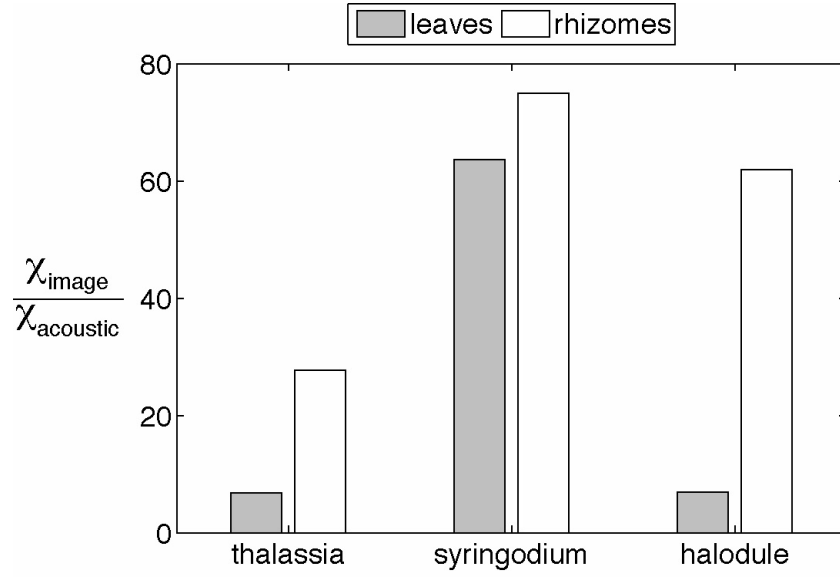


Fig. 11. *The ratio of the image-based to acoustically determined void fractions for both leaves and rhizomes of each species. This ratio is a measure of the importance of the tissue acoustic parameters. A ratio of unity indicates plants that behave acoustically like air bubbles in water. An increasing ratio indicates increasing tissue stiffness, which effectively reduces the acoustic contrast of the internal gas and also reduces the acoustic contrast of the plant.*

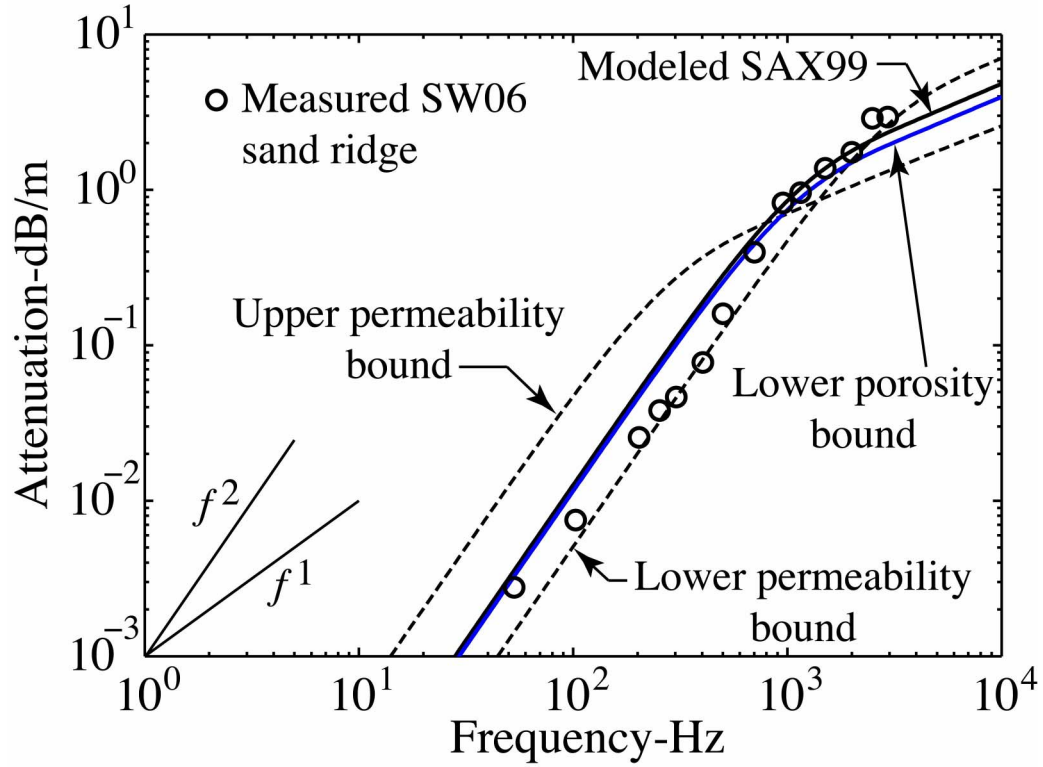


Fig. 12. The large purple triangles represent sandy sediment attenuation values inferred by matching measured long range transmission loss curves from SW06 with model predictions in which the sediment attenuation is the only fit parameter. The purple curve is the prediction of the EDFM with input parameters from SAX99. Note that these extrapolated attenuation values go below 100 Hz and clearly show a different slope than the higher frequency measurements.