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Impacts of simulated infaunal activities on acoustic wave propagation in marine sediments

Kelly M. Dorgan,1,a) Will Ballentine,1 Grant Lockridge,1 Erin Kiskaddon,1 Megan S. Ballard,2 Kevin M. Lee,2 and Preston S. Wilson2,b)

1Dauphin Island Sea Lab, 101 Bienville Boulevard, Dauphin Island, Alabama 36528, USA
2Applied Research Laboratories, 10000 Burnet Road, The University of Texas at Austin, Austin, Texas 78758, USA

ABSTRACT:
The activities of infaunal organisms, including feeding, locomotion, and home building, alter sediment physical properties including grain size and sorting, porosity, bulk density, permeability, packing, tortuosity, and consolidation behavior. These activities are also known to affect the acoustic properties of marine sediments, although previous studies have demonstrated complicated relationships between infaunal activities and geoaoustic properties. To avoid difficulties associated with real animals, whose exact locations and activities are unknown, this work uses artificial burrows and simulates infaunal activities such as irrigation, compaction, and tube building in controlled laboratory experiments. The results show statistically significant changes in sound speed and attenuation over a frequency range of 100–400 kHz, corresponding to wavelengths on the order of the burrow diameter. The greatest effects were observed for tubes constructed of hard shells which increased the attenuation by ~30 dB m⁻¹ across the measurement band. These results highlight the importance of biogenic hard structures such as tubes on sound attenuation and suggest that organisms that create hard structures may be good targets for acoustic mapping of infaunal abundance and distribution. © 2020 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1121/10.0000558

I. INTRODUCTION

Sonar provides an important tool for locating objects in marine sediments that are opaque to light waves as well as for non-invasively characterizing the geotechnical properties of sediments on broader spatial scales than would be feasible by mechanical means. Dependence of speed, attenuation, and scattering of acoustic waves on geotechnical properties of sediments has been well established (Chap. 5 in Jackson and Richardson, 2007). Speed of acoustic waves through sediments depends on porosity and bulk density; correlation between attenuation and porosity is less strong likely because attenuation depends on small-scale heterogeneity in sediment structure (Chap. 5 in Jackson and Richardson, 2007).

Most marine sediments (with anoxic areas as an exception) are inhabited by abundant and diverse infaunal organisms that substantially alter their physical environments through burrowing, construction and irrigation of tubes and burrows, and feeding on and defecation of sediments. Well established to be ecosystem engineers (Jones et al., 1994; Meysman et al., 2006), infauna alters surface roughness and stability, sediment porosity and permeability, and the physical structure of the sediment matrix (Eckman et al., 1981; Solan and Kennedy, 2002). Fauna can also modify grain distributions through selective feeding, resulting in graded beds (Rhoads and Stanley, 1965) or functionally coarsening sediments by ingesting fine grains and compacting them into fecal pellets (e.g., capitellid polychaetes) (Nowell et al., 1981). That biological structures can cause substantial deviation in acoustic properties from model predictions based on geotechnical properties alone is becoming increasingly apparent (Degraer et al., 2008; Jackson and Richardson, 2007), but the mechanisms by which burrowing and structure-building organisms alter the geotechnical and acoustic properties of sediments are not well understood. The goal of this study is to determine the impacts of burrows and tube structures on sound speed and attenuation in sediments.

The impacts of infauna on acoustic backscatter provide an opportunity for studying changes in organism distribution with much higher frequencies and on larger spatial scales than traditional methods allow. The tube-building polychaete, Lanice conchilega, is found in patches of high abundance in the North Sea; tubes extend above the sediment–water interface and trap particles, resulting in reef elevations ~9 cm higher than surrounding sediments (Degraer et al., 2008). Degraer et al. (2008) showed that these patches had high reflectivity and a patchy, grainy texture that could be detected and mapped with high-resolution (410, 445 kHz) side-scan sonar, but that only large, dense patches of worms could be detected with lower frequency (132 kHz) sonar. More recent work showed substantial annual fluctuations in Lanice conchilega distributions in the German Bight (North Sea) identified with side-scan sonar.
Tubes of infauna can vary substantially in composition, from mucus secretions comprising the entire tube with no embedded sediment grains (e.g., *Spiochaetopterus*) to thicker tubes comprised of compacted sediments glued together (e.g., maldanid and ampharetid polychaetes) (Jumars et al., 2015; Rouse and Pleijel, 2001). Some infauna exhibit strong selection for grains of certain sizes (e.g., pectinariid polychaetes, commonly known as ice cream cone worms for their characteristic rigid, cone-shaped tubes made from grains glued together). These different tubes likely affect sound waves very differently. Tubes of oweniid polychaetes such as *Owenia fusiformis*, which constructs a tube by gluing shell fragments in a shingled structure, likely have a relatively strong impact on sound propagation. These worms can actively alter the tube’s position, both vertically and laterally, and the tube generally extends 1–3 cm above the sediment surface (Eckman et al., 1981).

In addition to tube-building, infauna may modify sound propagation in sediments through burrow construction, in which sediments are excavated from burrows and deposited on the sediment surface and/or compacted into burrow walls. Fiddler crabs excavate some sediment from the burrows to the sediment surface, but some of the sediment is compacted into the burrow wall (Huang et al., 2007). Worms and other soft-bodied burrowers apply forces to burrow walls, causing burrows to extend by fracture and simultaneously compacting the burrow walls (Dorgan et al., 2005). Many burrowing animals also feed on sediments, and some effectively excavate by feeding on subsurface sediment and defecating on the surface (Jumars et al., 2015). Burrows are frequently irrigated to transport oxic overlying water down into anoxic burrows; in burrows with porous walls, e.g., lugworms, the extent of water penetration can depend on the permeability (Volkenborn et al., 2010). In more permeable, sandier sediments, water percolates through the sediment, whereas in less permeable, muddy sediments, pore water pressure can build up and water releases as plumes extending up from the sediment (Volkenborn et al., 2010).

Here we address the question of how these different infaunal behaviors affect the speed and attenuation of compressional waves in marine sediments. Experiments were conducted in silty, fine sands with sound speed ratios >1. We hypothesized that excavation and irrigation of burrows, which increase the water content of sediments, would shift the sound speed in sediment closer to that in water, i.e., move the ratio of sound speed in sediment to that of water closer to 1. We hypothesized that compaction would increase the sound speed if sound travelled through the compacted region of the burrow or have no effect if compaction decreases water content of the burrow walls but simultaneously increases water content within the burrow, thus having no net overall change. Finally, we hypothesized that structured shell tubes would increase sound speed if sound travelled through the denser tube walls.

Similarly, we hypothesized that excavation and irrigation would reduce attenuation by removing sediment grains that would scatter sound. Tube construction was predicted to increase attenuation through scattering by shell fragments. Compaction of burrow walls was also predicted to increase attenuation through scattering at the burrow wall interface, although to a lesser extent than the shell tube. Alternately, increased attenuation at the burrow wall interface could be countered by decreased attenuation in the open burrow, leading to a net zero effect.

Finally, we hypothesized that these effects would be greater at higher frequency and would vanish at low frequencies for which the wavelength was much greater than the size of the impacted region (the burrow diameter). We compared frequencies ranging from 100 kHz, slightly lower than the low-resolution side-scan sonar in which patches of the tube-building worm *Lanice conchilega* were difficult to detect, to 400 kHz, comparable to the high-resolution side-scan sonar that worked well at detecting and mapping worms (Degraer et al., 2008). These frequencies have corresponding wavelengths (3.75–15 mm) that span the range of burrow and tube diameters.

Preliminary experiments in which infauna from different functional groups, i.e., that impact sediment structure in different ways, were added to experimental cores showed attenuation that varied considerably as the core was rotated to measure different sections. Because the exact position of burrows was difficult to determine in opaque sediments, we were unable to link the presence or absence of a burrow with changes in sound speed or attenuation at a specific location in the core. We therefore simplified our experimental design and manipulated sediments to mimic these different burrowing behaviors. This allowed us to measure acoustic properties directly through and adjacent to the manipulated region of sediment. Specifically, we excavated cylindrical burrows, then either (1) compacted burrow walls, (2) irrigated the excavated burrow, or (3) inserted a cylindrical tube of shell fragments (to mimic *Owenia fusiformis* tubes), and measured the change in sound speed and attenuation resulting from each of these manipulations at three frequencies (100, 200, and 400 kHz).

II. METHODS
A. Overview

Sediments were homogenized, poured into PVC cores with caps on the bottom, degassed, and allowed to settle until sound speed and attenuation values reached a steady state. Cores were pre-scanned before manipulation to obtain baseline values, then burrows were excavated and cores were re-scanned. Excavated burrows were further manipulated in one of three ways: (1) compaction with an inflatable probe, (2) irrigation with perforated tube, or (3) insertion of a cylindrical tube of shell fragments, and then cores were scanned again.

Sound speed and attenuation were measured using a three-cycle sinusoidal tone burst at three frequencies: 100, 200, and 400 kHz. Cores were placed between a source
transducer and receiver, and sound speed was calculated from the time of flight, measured as the lag between the transmitted and received signals, through water and through sediment. Attenuation was calculated from the maximum amplitudes of the second of three positive-phase sinusoid half-cycles received through water and through sediment. Effects were calculated as the difference between the post-manipulation and baseline measurements.

B. Sediment core preparation

Sediment cores made from ~15.6 cm inner diameter PVC (sewer pipe) and cut to 17.5 cm long were closed at one end with a rubber cap and sealed with electrical tape. PVC wall thickness was 2.7 mm. Sediments were collected from the intertidal and shallow subtidal at Point aux Pins, AL. In the lab, sediments were homogenized in 2 L batches in a blender (1000 W Ninja Professional) for 2 min, then poured into prepared PVC cores. Half-filled cores were placed in a vacuum chamber and degassed at ~95 kPa for 2 h, then filled and placed in the vacuum chamber again for 22 h, resulting in 24 h total of degassing. Degassed cores were placed in an aerated seawater tank and allowed to settle for 20 to 30 days. This duration was determined by measuring sound speed and attenuation in cores every few days until the values reached steady state. Core diameter was chosen to allow for at least ten wavelengths at the lowest frequency used, 100 kHz ($\lambda = 15 \text{ mm}$), but to keep the distances small enough to avoid high attenuation.

C. Acoustic measurements

Acoustic measurements were made in a tank of seawater in the lab, following methods modified from Wilson et al. (2007). To prevent disturbance to the sediment structure, we opted to measure sound speed through the whole core with a source and one receiver rather than between two receivers that would have to be buried in the sediment [Fig. 1(A)]. This may result in underestimation of sound speed due to distortion of the signal by the source transducer (Buckingham and Richardson, 2002), but our focus was on the change in sound speed rather than absolute sound speed. This setup also allowed for measurements at multiple orientations within the same core. Olympus immersion transducers (V318-SU) were mounted on an aluminum frame at a distance of 24.3 cm, which exceeded the diameter of the core, leaving water between the transducers and core walls. This greater distance was chosen to approach the Raleigh distance at the highest frequency used, 30 cm for the 1.8 cm diameter transducer at 400 kHz, while also avoiding placing the transducers too close to the tank walls. The water space also prevented possible artifacts from putting the transducers in direct contact with the core wall. The transducers were mounted on a mobile frame that allowed for automated height changes. The sediment core was placed between the source and receiver on a turn table that rotated the core after each vertical scan (Fig. 1). Custom Matlab software controlled the height and orientation of measurements. This frame allowed for precise, repeatable, and computer-controlled positioning of acoustic measurements.

A three-cycle sinusoidal tone burst was generated using a HP 33120 A function generator, amplified with a Krohn-Hite model 7500 amplifier, and sent to the source transducer [Fig. 1(A)]. From the receiver, the signal was band-pass-filtered (±50 kHz) with a Krohn-Hite Model 34A dual channel filter in a Model 3905C multi-channel filter chassis before being captured by a Tektronix DPO 2014B digital oscilloscope at 500 MHz and recorded using custom Matlab software. For each measurement, 20 snapshots of the oscilloscope output were recorded, analyzed separately, and averaged. Sound speed and attenuation were measured at three depths [2.5, 5, 8 cm].
Sound speed and attenuation measurements in the sediment samples were calculated relative to those in seawater of the same temperature and salinity to obtain sound speed ratios. This also isolated the attenuation in the samples from the attenuation and geometric spreading of the signal through water. Acoustic measurements were performed on a seawater-filled PVC core for direct comparison with the measurements in sediment cores. Additionally, measurements were made with no core between the transducers to measure sound speed in water each day before measurements were done on sediment cores. Salinity of the seawater in the tank was adjusted to 14 ± 0.2 PSU to match the bottom water salinity where the sediment was collected. Water temperature ranged from 20.6 to 21.8 °C. Temperature and salinity were recorded each day. Seawater tanks in which cores were held between measurements were maintained at the same salinity and temperature. Sound speed calculated from measured temperatures and salinities for the 12 days of sampling ranged from 1501.6 to 1505.3 m s⁻¹. The calculated sound speed in water at the salinity and temperature for each day was used to check the measured distance between transducers by multiplying by the measured time of flight through water with no core between the transducers. This distance was 24.3 ± 0.1 cm (mean ± st. dev., n = 12) at 100 kHz (equal to the measured distance) and 24.0 ± 0.1 cm at 200 and 400 kHz. Sound speed was therefore calculated from the measured distance, 24.3 cm, divided by the time of flight. Sound speeds calculated from measured time of flight were more variable than and uncorrelated with sound speeds calculated from the varying temperature and salinity each day, so data from all 12 days were averaged to obtain the time of flight and peak amplitude in water at each frequency.

Sound speed ratio (SSR) was calculated from the time-of-flight measurements through sediment cores and the seawater-filled PVC core. Time of flight was calculated from the varying temperature and salinity each day, so data from all 12 days were averaged to obtain the time of flight and peak amplitude in water at each frequency.

![Image](https://doi.org/10.1121/10.0000558)

FIG. 2. The three-cycle sinusoidal tone burst transmitted and received signals from a representative measurement at 100 kHz through sediment.

with the temporal uncertainty, σₜ, determined by the 500-MHz sampling rate and the separation uncertainty, σ₅, estimated at 0.1 mm, following methods of Ballard et al. (2019):

$$\sigma_{ss} = \frac{c_w}{C_0} \left[ \frac{2\sigma_v^2}{d^2} + \frac{\sigma_d^2}{d^2} \left( \frac{\Delta t}{d} \right)^2 \right] \left( 1 - \frac{c_w \Delta t}{d} \right)^2.$$  

(2)

Using the separation distance between the source and receiver, d = 24.3 cm, the uncertainty due to measurement error is 0.03–0.04 m s⁻¹ across the three frequencies. This error is much smaller than the variability among measurements.

Attenuation (σₚ) [dB m⁻¹] was calculated from the maximum amplitudes of the second of the three positive-phase sinusoidal half-cycles in sediment (Pₛ) and in water (Pₚₚ) as

$$\sigma_p = \frac{20}{d} \log_{10} \left( \frac{P_w}{P_s} \right)$$  

(3)

(Jackson and Richardson, 2007). Attenuation in water is much smaller than attenuation in sediment. The first peak was much lower than the other two peaks, likely due to the response of the transducer (Fig. 2). The second peak was very close in amplitude to the third peak, thus appeared to be the most steady-state part of the signal. The peak amplitude in water (Pₛₙ₉₉) was measured with a seawater-filled PVC core between the transducers, which allowed us to account for the effect of the PVC core and the distance through the water on either side of the core (which primarily causes attenuation through geometric spreading).

The uncertainty in the estimated attenuation was determined from the propagation of error as

$$\sigma_2 = \frac{1}{d} \sqrt{\left( \frac{\sigma_{\Delta t}}{A_w} \right)^2 + \left( \frac{\sigma_{A_w}}{A_w} \right)^2 + \left( \frac{\sigma_d}{d \log_{10}(A_w/A_s)} \right)^2}.$$  

(4)

where $c_w$ is the sound speed in water, $\Delta t$ is $t_w - t_m$, the difference in time of flight between seawater-filled PVC core ($t_w$) and sediment cores ($t_m$) between the transducers, and $d_s$ is the inner diameter of the sediment core (15.35–15.78 cm), which was measured with calipers to 0.1 mm for each core orientation (Jackson and Richardson, 2007; Venegas et al., 2017). Sound speed in sediment (Eq. (1)) was then divided by $c_w$ to obtain the SSR.

The uncertainty in the estimated sound speed in sediment, $\sigma_{ss}$, was determined from the propagation of error, and 7.5 cm below the sediment–water interface (SWI), Figs. 1(A) and 1(B)] and at three frequencies (100, 200, and 400 kHz). Depths were chosen to avoid overlap of measurements with the 1.8 cm diameter transducer.
The uncertainty in the amplitude for water, $\sigma_{A_w}$, was calculated from the standard deviation of the amplitude of the second peak from 20 snapshots of the oscilloscope output. Standard deviation, $\sigma_{A_w}$, and mean amplitude, $A_w$, were calculated for three separate measurements and the ratios averaged for each of the three frequencies. Similarly, the uncertainty in the amplitude in sediment $\sigma_{A_s}$, was calculated in the same way for baseline measurements at 5 cm depth, and standard deviation and mean amplitude, $A_s$, were averaged across three cores. Uncertainty estimates were very small; 0.01, 0.03, and 0.08 dB m$^{-1}$ for 100, 200, and 400 kHz, respectively.

D. Manipulations to mimic infaunal activities

In each core, three burrow manipulations were done 2 cm from the core wall at $\pm 60^\circ$ angle from each other so manipulations did not interfere with measurements around the other two burrows in the core [Fig. 1(C)]. Measurements were done at three orientations: with the burrow directly between the transducers, and with the core rotated $13^\circ$ in each direction, which resulted in 2 cm distance along the outer edge of the core between measurements [Fig. 1(C)]. For these measurements, the path of sound passed a short distance away from the burrow wall [Fig. 1(C)]. These rotations allowed us to assess whether the impacts of burrows extended beyond the edges of the burrow or were more localized, potentially leading to high variability depending on whether a burrow was directly in the path of acoustic measurements. Acoustic measurements were taken pre-manipulation to establish baseline measurements, then 12-mm burrows were artificially excavated to 10 cm depth by inserting a 12-mm-diameter plastic straw [Fig. 3(A)]. Mud was removed from the straw by gently coring through the middle of the straw with a narrower, 8-mm-diameter straw. Once all sediment was removed, water was added to the straw to the height of the water above the core, then the straw was slowly removed. This allowed for excavation of a burrow without wall collapse or sediment compaction. Cores were then re-scanned, then burrows were further manipulated in one of three ways, irrigation, compaction, or shell tube addition, then scanned again to determine the effect of the manipulation (Fig. 3). Each of the three types of manipulations were repeated in six different cores.

To mimic irrigation, a straw of the same size used to create the burrow (12 mm) with slits cut along the sides and the bottom end sealed was inserted into the burrow [Fig. 3(B)]. 10 ml water was injected into the burrow to irrigate the surrounding sediment. Upon irrigation, a very small amount of fluidized sediment could be seen escaping the top of the burrow, indicating that most of the water was being forced into the surrounding sediments.

To mimic burrow compaction, an inflatable latex probe was constructed using liquid latex (Mehron Liquid Latex). Liquid latex was applied to the external surface of a solid cylinder (12 mm diameter, 13 cm length) that had been previously coated with a thin layer of water-soluble glue (Elmer’s Glue-All multi-purpose glue); the glue facilitated removal of the cured latex from the mold form without causing tears when submerged in water. With the cured latex form removed from the mold, a metal tube was fully inserted into the latex “balloon” and sealed around the top. When air was pushed through the metal rod, the latex inflated uniformly along the length of the probe without deforming. This probe was collapsed using a 60 ml syringe, inserted into the excavated burrow, and inflated with $\sim$10 ml of air to a diameter of 14 mm, thus compacting the burrow walls by 1 mm in radius. The probe was then collapsed and re-inflated two more times to compact the burrow walls [Fig. 3(C)].

Artificial shell tubes were constructed out of gelatin and shell hash of similar size to that in tubes made by oewniid worms. Natural worm tubes can vary considerably in length and width, but consistency in both parameters was

![FIG. 3. Schematic of the manipulations. (A) excavate burrow with straw (EX), (B) irrigation using straw with holes (IR), (C) compaction using inflatable balloon (COM) (D) shell “tube” inserted (ST).]
required for this manipulation so we opted for artificial tubes. Gelatin cylinders 8 mm in diameter were coated with a thin layer of liquid gelatin and then rolled in shell hash, creating a shelly tube with a final diameter of 12 mm. The shell tube was chilled to solidify, then recoated with gelatin, suspending the shells in a clear matrix. This recoating prevented air bubbles from being trapped around the shell fragments. Shell tubes were kept at 4°C until used. In preliminary experiments, shell was glued to a soda straw, but the straw alone increased attenuation, which was problematic. Gelatin is mostly water, so gelatin alone had no effect on acoustics. Use of gelatin also removed the need for adhesives that might affect sound propagation. Cold shell tubes were gently inserted into the excavated burrows and allowed to acclimate for 5 min before being scanned [Fig. 3(D)].

Impacts of these manipulations on SSR were calculated by subtracting the baseline measurement from the measurement following manipulation:

$$\Delta\text{SSR} = \frac{v_{p_{\text{man}}}}{c_w} - \frac{v_{p_{\text{BL}}}}{c_w},$$

(5)

where $v_{p_{\text{man}}}$ is the sound speed following the manipulation and $v_{p_{\text{BL}}}$ is the baseline sound speed [Eq. (1)]. For attenuation, the change in attenuation ($\alpha_{\text{man}}$) was calculated as

$$\alpha_{\text{man}} = \frac{20}{d} \log_{10} \left( \frac{P_{\text{BL}}}{P_{\text{man}}} \right),$$

(6)

where $P_{\text{BL}}$ is the baseline peak height and $P_{\text{man}}$ is the peak height following the manipulation. Comparing the post-manipulation sound speed and amplitude to the baseline for each manipulation allowed us to account for variability among cores.

E. Porosity and grain size

After the manipulations and acoustic measurements were complete, samples for porosity and grain size measurements were taken from each sediment core using a modified syringe to take a 2.5 cm diameter sub-core. These sub-cores were then extruded from the syringe, and 2-cm long samples were taken centered at the depths at which the cores had been scanned. Porosity ($p$) was measured for each depth in each core as $p = V_w/V_t$. $V_w$ is volume of the water removed from each sediment upon drying, and $V_t$ is the total volume of the sample. Grain size analysis was done on a Malvern Mastersizer 3000 on subsamples from two depths (2.5 and 7.5 cm) in three cores.

III. RESULTS

A. Porosity and grain size

Porosity varied from 0.42 to 0.54 (0.48 ± 0.03; mean ± st. dev., $n = 27$) at all depths in all cores but showed no depth dependence (linear regression, $p = 0.88$). There was no difference in grain size distribution among cores or with depths in a core. Sediments were fine-skewed, moderately sorted, fine sands with 91.4% sand, 8.6% silt based on the Wentworth scale and $d_{50} = 129\mu m$.

B. Baseline sound speed and attenuation

There was overlap in the acoustic propagation paths at different orientations within a depth in a core, so data were not truly independent. Both SSR and attenuation showed less variability among orientations at a given depth within a core than among different depths in each core. Thus, orientations were averaged for each depth in each core to further examine baseline data (Fig. 4). There was no clear pattern in sound speed or attenuation among cores, i.e., no effect of the order in which cores were run in the experiment. One core had much higher attenuation as well as a higher SSR at all orientations than other cores at 100 kHz at 7.5 cm depth so those data were removed from the analysis.

Baseline SSR was not correlated with porosity for the narrow range of porosities measured ($p < 0.1$ for all frequencies; Fig. 4(A)). SSR increased with depth in the core at 200 and 400 kHz (linear regression, $p < 0.01$, $R^2 = 0.55$ and 0.67, respectively) but not at 100 kHz ($p = 0.07$, $R^2 = 0.13$) [Fig. 4(C)]. Sound speed ratios were higher at higher frequency indicating dispersion [Figs. 4(A) and 4(C)].

Baseline attenuation increased slightly with porosity at 100 kHz ($p = 0.055$, $R^2 = 0.15$), but was not correlated with porosity at 200 or 400 kHz for the narrow range of porosities measured ($p > 0.1$) [Fig. 4(B)]. Attenuation increased with depth in the core at 200 and 400 kHz (linear regression, $p < 0.01$, $R^2 = 0.31$ and 0.25, respectively) but not at 100 kHz ($p = 0.14$, $R^2 = 0.09$) [Fig. 4(D)]. Attenuation also increased with frequency [Figs. 4(B) and 4(D)].

C. Effect of excavation

Outliers that deviated substantially from other points (>2 std from mean) were removed, leaving 23–25 replicates. Burrow excavation decreased SSR from the baseline value at all depths for 200 and 400 kHz (Fig. 5, Table I). At higher frequencies, this effect was most significant for the center straight orientation and decreased or disappeared for many of the 13° angle measurements. At 100 kHz, the effects did not differ among the three orientations. The effect increased slightly with depth at 100 kHz, with no significant effect at 2.5 cm depth. These effects at all frequencies were very small, however, only ~0.1% change in SSR (Table I).

No effects on attenuation were observed at 100 kHz; attenuation was lower at 200 and 400 kHz but not significantly lower at 7.5 cm depth (Fig. 6). The effect on attenuation disappeared at the rotated (±13°) orientations. This decrease in attenuation was >2% of the baseline attenuation at the higher frequencies (Table I).

D. Effect of manipulations

The effects of subsequent manipulations are presented relative to baseline values, but because irrigation, compaction, and shell tube insertion were done after the excavation,
it is useful to compare manipulation values to excavation
effects (horizontal dashed lines, Figs. 5 and 6) as well as the
baseline (solid line at 0 in Figs. 5 and 6). The effects on
sound speed were small for all manipulations (note vertical
scale in Fig. 5); for no manipulations were the effects
>0.5% of the baseline SSR (Table I). Irrigation did not
decrease SSR beyond the effect of excavation at any fre-
quency (Fig. 5). At 400 kHz, irrigation effects were similar
to those of excavation, with greater impact at the straight
than rotated orientations, but there was no effect of irrigation
further decreasing SSR as predicted [Fig. 5(C)]. At
200 kHz, the effect of irrigation fell between that of excavation
and the baseline, not significantly different from either
[Fig. 5(B)]. At 100 kHz, the effect of irrigation was similar
to or slightly higher than that of excavation, with higher
variability in the rotated orientations [Fig. 5(A)].
Compaction had a similar effect to irrigation, with effects
not different from baseline but sometimes slightly greater
than excavation (Fig. 5). The shell tube treatment did not
differ from the baseline value at straight orientations, other
than at 5 cm depth at 200 kHz [Fig. 5(B)] where SSR was
slightly higher than baseline. SSR for the shell tube
treatment was slightly higher than or comparable to SSR
following excavation (dashed line; Fig. 5).

Attenuation increased significantly with addition of the
shell tube at all frequencies and depths (Fig. 6). Attenuation
decreased significantly from baseline values following irriga-
tion and compaction at 200 and 400 kHz, although this effect
was in most cases not different from the initial excavation
(dashed line, Fig. 6). Neither irrigation nor compaction
affected attenuation at 100 kHz [Fig. 6(A)]. Effects of manipu-
lations on attenuation in the rotated orientations were gener-
ally smaller and more variable than the straight orientations
(Fig. 6), although the shell tube increased attenuation at one of
the rotated orientations at all frequencies and depths. Baseline
attenuation increased with frequency (Fig. 4), so the increase
in attenuation of \( \sim 30 \text{ dB m}^{-1} \) due to shell tubes at all frequen-
cies was proportionally greater at 100 than 400 kHz (Table I).

Outliers that deviated substantially from other points
(\( \geq 2 \text{ std from mean} \)) were removed, leaving 4–7 replicates
for each manipulation treatment. The shell tube manipula-
tion in one core had multiple outliers at different frequen-
cies and depths, so the whole replicate was removed from
analysis. Error bars showing 95% confidence intervals are

![Graphs](https://doi.org/10.1121/10.0000558)
smaller for excavation (Figs. 5 and 6) because the sample size is larger (n = 23–25 vs n = 4–7 for manipulations).

IV. DISCUSSION

Both sound speed ratios and attenuations measured in this study are within the range of measurements from previous studies (Fig. 7). Sound speed ratios are inversely correlated with porosity for sandy sediments, with that relationship leveling off for muddier sediments (Fig. 7; Jackson and Richardson, 2007). Our data fit the prediction of sound speed ratios for the range of porosities in our study based on an empirical fit from previous data [Fig. 7(A)]. Our attenuation measurements were high but within the range of previous studies [Fig. 7(B)].

TABLE I. Sound speed ratio (SSR) and attenuation (dB m⁻¹) for baseline measurements and the four manipulations at the middle depth of 5 cm. Mean values as well as the absolute change from baseline value and the percent change from baseline values are presented. Changes from baseline were calculated for each orientation within each core, then cores were averaged. Baseline values were obtained by first averaging nine orientations in each core, then averaging cores (n = 8–9). Values are means ± 95% confidence intervals of n cores. * indicates significant effects.

| Manipulation | Freq (kHz) | SSR    | Change in SSR | Attenuation (dB m⁻¹) | Change in attenuation (dB m⁻¹) | Change in attenuation (%) n |
|--------------|------------|--------|---------------|-----------------------|---------------------------------|-----------------------------|
| Baseline     | 100        | 1.0437 ± 0.0021 |                 | 95.1 ± 3.9            |                                  |                             |
| Excavation   | 100        | 1.0430 ± 0.0021 | -0.0007 ± 0.0005 | 94.7 ± 0.7          | -0.3 ± 0.7                      | -0.29 ± 0.67                |
| Irrigation   | 100        | 1.0418 ± 0.0063 | 0.0011 ± 0.0007 | 97.7 ± 5.9          | 0.1 ± 5.3                       | 0.51 ± 5.48                |
| Compaction   | 100        | 1.0436 ± 0.0046 | 0.0008 ± 0.0019 | 96.1 ± 4.9          | -1.3 ± 3.3                      | -1.23 ± 3.05                |
| Shell tube   | 100        | 1.0457 ± 0.0024 | 0.0006 ± 0.0020 | 129.4 ± 6.9         | 29.6 ± 3.9                      | 29.88 ± 4.34                |
| Baseline     | 200        | 1.0596 ± 0.0014 |                 | 202.5 ± 14.6        |                                  |                             |
| Excavation   | 200        | 1.0582 ± 0.0015 | -0.0013 ± 0.0003 | 196.3 ± 1.9         | -5.6 ± 1.9                      | -2.63 ± 0.85                |
| Irrigation   | 200        | 1.0603 ± 0.0059 | -0.0005 ± 0.0004 | 197.0 ± 1.7         | -9.2 ± 4.0                      | -4.40 ± 1.81                |
| Compaction   | 200        | 1.0573 ± 0.0065 | 0.0007 ± 0.0021 | 181.9 ± 54.8        | -5.9 ± 2.4                      | -3.50 ± 2.32                |
| Shell tube   | 200        | 1.0631 ± 0.0013 | 0.0011 ± 0.0010 | 221.9 ± 26.6        | 20.7 ± 9.1                      | 9.88 ± 3.33                |
| Baseline     | 400        | 1.0696 ± 0.0017 |                 | 290.1 ± 18.9        |                                  |                             |
| Excavation   | 400        | 1.0682 ± 0.0015 | -0.0015 ± 0.0005 | 282.8 ± 3.8         | -6.7 ± 3.8                      | -2.27 ± 1.24                |
| Irrigation   | 400        | 1.0712 ± 0.0051 | -0.0018 ± 0.0007 | 291.9 ± 10.6        | -17.6 ± 5.6                     | -5.72 ± 1.92                |
| Compaction   | 400        | 1.0692 ± 0.0021 | -0.0004 ± 0.0006 | 276.9 ± 24.5        | -9.8 ± 1.7                      | -3.44 ± 0.75                |
| Shell tube   | 400        | 1.0707 ± 0.0029 | 0.0001 ± 0.0009 | 322.8 ± 25.2        | 18.8 ± 8.4                      | 6.15 ± 2.47                |

FIG. 5. (Color online) Change in SSR relative to baseline values at (A) 100 kHz, (B) 200 kHz, and (C) 400 kHz resulting from the four manipulations. Plots are shown for 2.5 cm (top), 5 cm (middle), and 7.5 cm (lower) below the sediment–water interface. The straight orientation is shown as a filled symbol, 13° rotated orientations as open symbols. Excavation data are shown for all burrows (n = 23–25) and the dashed horizontal line marks the mean value (error bars are 95% CI). Manipulations following the excavation are plotted to the right of the vertical dotted line (n = 4–7); change is calculated relative to baseline measurements.
FIG. 6. (Color online) Change in attenuation (dB m$^{-1}$) relative to baseline values at (A) 100 kHz, (B) 200 kHz, and (C) 400 kHz resulting from the four manipulations. Plots are shown for 2.5 cm (top), 5 cm (middle), and 7.5 cm (lower) below the sediment–water interface. The straight orientation is shown as a filled symbol, 13° rotated orientations as open symbols. Excavation data are shown for all burrows ($n = 23–25$) and the dashed horizontal line marks the mean value (error bars are 95% CI). Manipulations following the excavation are plotted to the right of the vertical dotted line ($n = 4–7$); change is calculated relative to baseline measurements.

FIG. 7. (Color online) (A) SSR, and (B) attenuation plotted as a function of porosity for our measurements of baseline (cyan stars) and manipulated (other large symbols with error bars showing standard deviation) SSR and attenuation (dB m$^{-1}$kHz$^{-1}$) relative to data collected for a range of natural sediments (Buckingham, 2005, and references therein). Data compiled by Buckingham (2005) were collected at multiple different frequencies. The solid line in (A) is an empirical quadratic fit to the historical data of the form SSR($\rho$) = 1.2379*$\rho^2$ – 1.8364*$\rho$ + 1.6593, where $\rho$ is porosity.
The increase in baseline SSR with depth in the core for 200 and 400 kHz (Fig. 4) is consistent with higher sound speed at greater depths observed by Buckingham (2005). This does not appear to be due to a gradient in porosity due to compaction as sediments consolidated, as porosity did not change with depth and the range in porosity was quite small. Sandy sediments in the SAX99 experiment off the Florida Panhandle also had constant porosity with depth (∼36%) and increasing sound speed and attenuation (Richardson et al., 2001). That porosity did not increase with depth in our muddier sediments is somewhat surprising, and may result from homogenization of sediments before the experiment; settlement time may not have been long enough to compact subsurface sediments. Greater attenuation at higher frequencies is consistent with previous studies (Hamilton, 1976; Jackson and Richardson, 2007).

Burrow excavation had a small but statistically significant effect on both sound speed and attenuation, consistent with our predictions that increased water content would decrease both SSR and attenuation. Our data also supported our hypothesis that this effect would be greater for higher frequencies (400 kHz) with wavelengths smaller than the burrow diameter but would be less at lower frequencies (100 kHz) when wavelengths were larger than the burrow hole. The burrow diameter used is larger than burrows created by most infauna, but within the range of burrows made by very large polychaete worms, large clams, and burrowing shrimp.

None of the manipulations had a substantial effect on sound speed, with changes <0.5% of the SSR for all manipulations (Fig. 5). These relatively small changes in the SSR, on the order of 0.001, mostly fall within the error bars of variability among different orientations within a depth of a core [cf. Figs. 4(A) and 5] and are small relative to the variability in sound speed as a function of porosity [Fig. 7(A)]. The magnitude of this effect is predicted considering the size of the burrow relative to the core: removing a 1.2 cm diameter “burrow” from a 15.6 cm sediment path produces an effective SSR of \( v_{\text{eff}} = v_p [(15.6 - 1.2)/15.6] + c_w (1.2/15.6). \) For \( v_p = 1.05, \) the effective SSR is 1.046. This difference of 0.004 is very close to the decrease of 0.001–0.002 in SSR observed (Fig. 5). This suggests that increasing the number of burrows along the acoustic path will cause the SSR to decrease with increasing portion of the acoustic path associated with burrows.

Following this same logic, removal of sediment from burrows should decrease attenuation by increasing the effective peak amplitude of the received signal as \( P_{\text{eff}} = P_{\text{BL}}[(15.6 - 1.2)/15.6] + P_w (1.2/15.6). \) Amplitudes vary considerably among the three frequencies both in water and in sediment, so \( P_{\text{eff}} \) was calculated for each frequency and converted to attenuation using Eq. (6) (with \( P_{\text{eff}} \) replacing \( P_{\text{man}} \)). These predicted changes in attenuation were −17, −75, and −151 dB m\(^{-1}\) for 100, 200, and 400 kHz, respectively. Measured decreases in attenuation from excavation, irrigation, and compaction were substantially smaller than these predicted values. Although these manipulations reduced the path length through sediment, the effect of removing sediment on peak amplitude is much less than predicted from path length alone. This could be due to the wavelength being comparable in size to the burrows, leading to complex interactions with burrow walls that likely increase scattering.

We expected irrigation to decrease attenuation, the shell tube to increase attenuation, and compaction falling in between the two, but in fact we found a sharp difference between the shell tube and the other manipulations in their effects on attenuation. The shell tube increased attenuation as hypothesized, but the increase of ∼30 dB m\(^{-1}\) was substantially greater than the effects of the other manipulations (Fig. 6). Moreover, this difference is substantial in the context of variability in attenuation from other studies, indicating that biological structures such as shell tubes could explain some of the high variability in sound speed as a function of porosity [Fig. 7(B)]. This is consistent with studies showing enhanced backscatter from the sandy tubes of Lanice conchilega (Degraer et al., 2008). We expected that the compaction of burrow walls would affect sound more similarly to the shell tube; many worms build tubes of compacted sediments or compact burrow walls to create semi-permanent burrows (Jumars et al., 2015). The compaction treatment, however, did not change the attenuation from the initial excavation; if anything, the compaction decreased attenuation further rather than increasing attenuation through burrow wall scattering (Fig. 6). It is possible that decreased attenuation occurred because the closer contact of particles following compaction allows the waves to propagate with less loss. This possibility is intriguing, as it suggests that compacted burrow walls and tubes may have distinct effects on acoustics rather than falling along a continuum of impacts. We expected irrigation to decrease attenuation beyond the impact of excavation, and there was a trend toward lower attenuation at 400 kHz, but the effect was not significantly different from excration (see overlapping confidence intervals in Fig. 6). We did not quantify the effect of our irrigation and compaction manipulations on sediment porosity, and it is possible that irrigation with a larger volume of water or more prolonged or higher pressure compaction would have more of an impact. The permeability of sediment dictates the fate of water pumped into burrows (Volkenborn et al., 2010), so the irrigation manipulation results do not necessarily translate to sandier or muddier sediments.

The increase of ∼30 dB m\(^{-1}\) in attenuation from the shell tube was consistent across all frequencies rather than increasing at higher frequencies as we expected (Fig. 6). In contrast, the decrease in attenuation caused by the other manipulations was higher at 400 than 200 kHz and was not present at 100 kHz, consistent with our hypothesis. Baseline attenuation increases with frequency, so the impact of infauna at higher frequencies than used here would likely be very small compared to the high baseline attenuation. These experiments are limited to frequencies low enough to avoid multiple scattering effects that occur when the
wavelength approaches the mean grain size. Thus, there may be an intermediate range of frequencies in which sound attenuation by infauna is most detectable, with wavelengths corresponding to lower frequencies being too large to be impacted by heterogeneities on the scale of fauna and scattering of sound at higher frequencies by grains overwhelming the impacts of fauna.

Shell tubes affected attenuation even at our lowest frequency with corresponding wavelength larger than the tube diameter, indicating that structured shell tubes may be particularly important as biogenic effects on sound propagation. This was somewhat surprising, as habitat mapping with sidescan sonar did not work as well at lower frequencies (132 kHz) as with higher resolution (410 kHz) (Degraer et al., 2008). Our tube mimics were considerably larger than tubes of *Lanice conchilega*, which could explain these differences, although Degraer et al. (2008) were studying worms in relatively large, clustered patches in contrast to our single tubes. Our experiment measured subsurface sound propagation rather than scattering, and it is possible that backscatter may be more sensitive to frequency dependence. Our shell tubes were intended to mimic those made by *Owenia fusiformis* but were slightly larger in diameter than natural *Owenia* tubes for comparison with the other manipulations, and it is likely that smaller natural tubes would have less impact at lower frequencies. On the other hand, the shell fragments in natural tubes are much more structured than those in our tube mimics, which might enhance scattering. Whether shell fragments in *Owenia* tubes affect sound differently than the compacted sand tubes of *Lanice conchilega*, *O. fusiformis* can be found in fairly dense patches, so would be a good target for habitat mapping with sidescan sonar.

V. CONCLUSIONS

Infaunal organisms build structures such as tubes and burrows that modify acoustic properties of marine sediments. This experiment was a very simplified first step toward developing a mechanistic understanding of these effects, examining how one single burrow or tube affects sound speed and attenuation. Effects on sound speed were small but consistent with predictions calculated by reducing the transmitted path length by the diameter of the burrow, indicating that infauna influence sound speed through changes in bulk density and that these effects may be additive for multiple burrows. Infaunal activities have more substantial effects on attenuation, with excavation, irrigation, and compaction all decreasing attenuation at higher frequencies and the effect decreasing or vanishing at lower frequencies with wavelengths larger than the burrow diameter. These effects were much smaller than calculated by reducing the transmitted path by the burrow diameter, consistent with a more complex dependence of attenuation on heterogeneities in sediments. The effects of shell tubes on attenuation were distinct from the other manipulations both in the larger magnitude of the increase in attenuation (Figs. 6 and 7) and its frequency independence.

This experiment did not capture the effects of multiple burrows or tubes interacting, which is especially important since many organisms have patchy but abundant distributions, resulting in clustered tubes and burrows. We also did not mimic the effect of bioturbation, the mixing of sediments by burrowing fauna, which can modify porosity and bulk density (Jackson and Richardson, 2007). Our results suggest that isolated heterogeneity created by organisms has a much greater impact on attenuation than on sound speed, and that structured tubes should be targets of future research on the impacts of infauna on sediment acoustics.

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