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Key Points:
• This study measured the high-frequency acoustic properties for fine sandy sediments using in situ method and laboratory method
• This study compared the measured acoustic property to the empirical equation predictions
• This study established the frequency dependence of acoustic properties and carried out the model-data comparison

Abstract The object of this study was to obtain the acoustic properties of fine sandy sediments with approximately 22% clay content from the East China Sea Shelf. This study conducted the in situ acoustic measurement to measure the sound speed and attenuation, and eight sediment cores were collected and measured the wet bulk density, porosity, and mean grain size in laboratory environment. The correlations between in situ sound speed ratio and physical properties show good accordance with two empirical equations, while the in situ attenuation factor deviated the regression curves. Both the sound speed ratio and the attenuation data show the obvious change against the measurement frequency. The comparisons of the measured sound speed ratio and attenuation to the Biot-Stoll model predictions were performed. The sound speed ratio dispersion agrees well with the model prediction, when the permeability and pore size were calculated using the extended Kozeny-Carman's equation and the extended Howem's equation. The attenuation data in this study accords better with the prediction curves reported for fine sediments than that for coarse sediments from the 1999 Sediment Acoustics Experiment.

1. Introduction

The acoustic properties of seafloor sediments can be used for modeling sea-bottom reflection and scattering and also are significant in several other fields, such as underwater engineering and geophysical research (Jackson & Richardson, 2007). The acoustic measurements can provide basic data to establish empirical equations for predicting acoustic properties of seafloor sediments (Gettemy & Tobin, 2003; Liu et al., 2013). The methods to measure the sound speed and attenuation in seafloor sediments mainly consist of in situ measurement methods (Hefner et al., 2009; Lee et al., 2016; Yang & Tang, 2017), laboratory measurement methods (Kim et al., 2013; Mendoza et al., 2014; Sessarego et al., 2008), and remote sensing methods (Bonnel & Chapman, 2011; Li et al., 2014). These methods have different measuring frequency for acoustic properties, and the comparisons among the measurement results using different frequency should be considered.

Many studies have focused on the frequency dependence of sound speed and attenuation within the frequency range from a few hundred of hertz up to a few thousand of kilohertz (Zimmer et al., 2010) and used the measured data to assess the applicability of the geoacoustic propagation models, including Biot-Stoll model (Chotiros & Isakson, 2004; Nosal et al., 2008), EDFM model (Williams, 2001; Yu et al., 2017), GS and VGS models (Ballard & Lee, 2016; Buckingham, 2005). Biot theory focused on the relative motion between the framework and the pore fluid (Biot, 1956a, 1956b) and can be expressed as Biot-Stoll model with a number of input physical parameters, including permeability, porosity, pore size, and tortuosity, as well as bulk modulus and density of sediment grains, bulk modulus, density, and viscosity of the pore fluid (Stoll, 1998; Stoll & Baustia, 1998). The 1999 Sediment Acoustics Experiment has suggested that the acoustic wave is dispersive in sand and is generally consistent with Biot theory predictions in a broad band of frequencies (Hines et al., 2010; Williams et al., 2002). A number of investigators continued the studies on measurement and modeling the sound speed and attenuation frequency dependence in different frequency bands for various seafloor sediments, compared their measurement results to the model predictions, and have found that the Biot-Stoll model could not always predict the attenuation frequency dependence accurately due to lack of effective model input parameters. Furthermore, since most of these measurements were conducted in coarse sand sediments or water saturated glass beads (Kimura, 2011), the acoustic properties in fine-grained sediments such as fine sands or muddy sediments still need to be measured more targeted and more synthetically.
In this study, the first objective is to show the measured acoustic properties of fine sandy sediments over the frequency range of 30–87 kHz using in situ methods and laboratory methods, and their relationship with the synchronously acquired physical properties. The second objective is to present the frequency dependence of sound speed ratio and attenuation in fine-grained sandy sediments, which will be compared to the Biot-Stoll model predictions.

2. Materials and Methods

The study area was located in the East China Sea shelf (25–30°N, 122–125°E), and the sediment source mainly consists of the terrigenous sediments from the Yangtze River and Yellow River. The central shelf sedimentary area includes most of the continental shelf between 50- and 120-m depth contour. The sediment composition is complex and the main sediment type is the sandy silt sediment and the silty sand sediment. The surface sediments are rich in shell fragments, showing a film-grey color, and the mean grain size is between 4ϕ and 5ϕ. There were eight sediment cores collected using a sediment core collector carried on the BISAMS (ballast in situ sediment acoustic measurement system), the sediment cores were 11.0 cm in diameter and 17–40 cm in length. Two separate measurement systems were used to measure the sound speed and attenuation over a frequency range from 30 to 87 kHz, including the BISAMS at frequency of 30 kHz, and a sediment core measurement system for frequencies from 47 to 87 kHz. These two acoustic measurement systems would be introduced in section 2.1.

2.1. In Situ Sediment Acoustic Measurement

The BISAMS has been introduced in detail in Wang et al. (2018), as shown in Figure 1. The BISAMS uses a ballast penetrating method to insert the acoustic transducers into seaﬂoor sediments. The transducer probes could drive down into the seabed extending 30 cm after the system was placed onto the seaﬂoor. The transmitting transducer was driven with tone bursts of five cycles at frequency 30 kHz. The acoustic signal time series were recorded 12 times for each station at a 10 MHz sampling rate with a high-speed digital recording system. The time series of the recorded signals are shown in Figure 2a, which are collected in the seawater column, and in Figure 2b, which are collected in the sediments.

The distances between the transmitting transducer and three receiving transducer are approximately \( AB = 0.6 \) m, \( AD = 0.8 \) m, and \( AC = 1 \) m, respectively, and the accurate differences between two of the three propagation paths could be calibrated while the BISAMS was employed in water column, by measuring the sound speed of seawater and calculating the time delay between the waveforms recorded by two of the three

![Figure 1](image1.png)

**Figure 1.** The mechanical structure, the acoustic transducers arrangement, and the acoustic signal propagation paths of ballast in situ sediment acoustic measurement system.

![Figure 2a](image2a.png)  ![Figure 2b](image2b.png)

**Figure 2.** The received acoustic signals from the three different received transducers of ballast in situ sediment acoustic measurement system in seawater and in sediments.
receiving channels, using cross correlation method. The sound speed of sediments $V_p$ can be calculated according to the following equation:

$$ V_p = \frac{t_w V_w}{t_p} = \frac{V_w}{1 - \frac{V_w (t_w - t_p)}{d}} $$

(1)

where $V_p$ is the sound speed in sediment in m/s; $V_w$ is the sound speed in seawater in m/s; $d$ is the distance between the transmitting transducer and the receiving transducer in meters; $t_w$ and $t_p$ is the travel time difference of acoustic signals received by the different receiving transducers in seawater and in sediment, that is, $t_{w1} = t_{wAD} - t_{wAB}$, $t_{w2} = t_{wAC} - t_{wAB}$, or $t_{w3} = t_{wAC} - t_{wAD}$, where $t_{wAB}$, $t_{wAC}$, and $t_{wAD}$ are the travel times of acoustic signals arriving at the three receiving transducers in seawater. The travel time difference $t_w$ and $t_p$ can be calculated using the cross-correlation method or the peak-peak method. The sound speed in seawater was measured using a sound velocity profiler with high measurement precision. The sound speed ratio was calculated as the ratio of the sediment sound speed $V_p$ to the bottom seawater sound speed $V_w$ measured using sound velocity profiler. The differences in distance between the transducers were calculated as

$$ d_1 = \overline{AD} - \overline{AB} = t_{w1} V_w $$

(2)

$$ d_2 = \overline{AC} - \overline{AB} = t_{w2} V_w $$

(3)

$$ d_3 = \overline{AD} - \overline{AC} = t_{w3} V_w $$

(4)

The accurate distance differences were repeatedly corrected at each station, $d_1 = 20.46$ cm, $d_2 = 19.39$ cm, and $d_3 = 39.83$ cm.

Bias error can occur in the calculation of the cross correlation time delay because the received waveform by different receiving transducer do not have the same shape in the absence of dispersion and attenuation of acoustic signals, which can lead to inaccuracy in the calculation of travel times or travel time differences (Lee et al., 2017). To account for the bias error, first, the uncertainty of travel time difference in the seawater was calculated using the difference between the peak-peak time difference of signals and the time delay obtained from the cross correlation, $\sigma_{t_{w1}} = 0.3$ $\mu$s, $\sigma_{t_{w2}} = 0.3$ $\mu$s, and $\sigma_{t_{w3}} = 0.5$ $\mu$s, respectively. The uncertainty of travel time difference in sediment were of the same calculation method as that in the seawater. The uncertainty in the distance difference between transmitting and receiving transducer is given by $\sigma_{d_i} = 0.15$ cm, $\sigma_{d_2} = 0.15$ cm, and $\sigma_{d_3} = 0.14$ cm, respectively. From equation (A1) and propagation of error, the uncertainty in the sound speed calculation is given by

$$ \sigma_{v_i} = V_p^2 \left( \frac{\sigma_{t_{w1}}^2}{d_1^2} + \frac{\sigma_{t_{w2}}^2}{d_2^2} + \frac{(t_{w3} - t_{p3})}{d_3^2} \right)^{1/2} $$

(5)

where $i = 1, 2, 3$, respectively. $d$ is the distance difference between three receiving transducers in meters. In this study, the uncertainty in the sound speed calculation at each signal propagation path $\sigma_{v_1}$, $\sigma_{v_2}$, and $\sigma_{v_3}$ was 5.33, 5.61, and 4.53 m/s, respectively, when the travel time difference of signals $t_{w1}$, $t_{w2}$, and $t_{w3}$ was 6.8, 6.4, and 12.9 $\mu$s, respectively, and the average value of $V_p$ was 1.596.26 m/s for the sediments. The attenuation was calculated from the base-10 logarithm of the ratio of the received amplitude in the seawater to that in the sediments. The geometrical spreading for each propagation path is assumed to be equal since the distance between transducer probes remained constant whether the system measurement in seawater or in sediments. The attenuation coefficient $\alpha_s$ can be calculated using the following formula:

$$ \alpha_p = \frac{20}{l} \times \log \frac{A_w}{A_p} $$

(6)

where $\alpha_p$ is the acoustic attenuation coefficient in dB/m; $l$ is the distance between the transmitting transducer and the receiving transducer in meters; and $A_p$ and $A_w$ are the peak magnitudes of the acoustic signals in sediment and in seawater received by the receiving transducers, respectively.
The distance difference error $\sigma_d$ and the amplitude measurement error $\sigma_{Ap}$ for sediments and $\sigma_{Aw}$ for seawater lead to the bias error in the attenuation calculation. The amplitude error $\sigma_{Ap}$ and $\sigma_{Aw}$ were estimated from the standard deviation of the peak amplitude for the seawater and sediments, respectively. The $\sigma_{Aw1}$ is 0.015, $\sigma_{Aw2}$ is 0.102, and $\sigma_{Aw3}$ is 0.028, when $A_{w1}$ is 4.375, $A_{w2}$ is 3.806, and $A_{w3}$ is 3.252. The $\sigma_{Ap1}$ is 0.024, $\sigma_{Ap2}$ is 0.025, and $\sigma_{Ap3}$ is 0.018, when $A_{p1}$ is 2.084, $A_{p2}$ is 1.051, and $A_{p3}$ is 0.735. From equation (A6) and propagation of error, the uncertainty in the attenuation calculation is given by

$$\sigma_{\alpha_p} = \frac{20}{l_i} \sqrt{\left( \frac{\sigma_{Aw}}{A_{wi}} \right)^2 + \left( \frac{\sigma_{Ap}}{A_{pi}} \right)^2 + \left( \frac{\sigma_l}{l_i} \right)^2 \log \left( \frac{A_{wi}}{A_{pi}} \right)^2}$$  \hspace{1cm} (7)

where $i = 1, 2, 3$, respectively. The distance between the transmitting transducer and the receiving transducer $l_1, l_2$, and $l_3$ was 60, 80, and 100 cm. In this study, the uncertainty in the attenuation calculation at each signal propagation path $\sigma_{\alpha_1}, \sigma_{\alpha_2}$, and $\sigma_{\alpha_3}$ was 0.19, 0.61, and 0.68 dB/m, respectively, when the uncertainty in the distance $\sigma_{l1}, \sigma_{l2}$, and $\sigma_{l3}$ was 0.25, 0.52, and 0.86 cm, respectively, and the average value of $\alpha_p$ was 11.08 dB/m for the sediments.

### 2.2. Sediment Core Acoustic Measurement

The sediment cores were collected and stored shipboard. The sound speed and attenuation measurements were made on each core using four separate pairs of acoustic transducers with center frequency of 47, 52, 75, and 87 kHz, respectively. After the sediment core was placed on a test platform, each pair of transducers was placed on either side of the sediment core. The transmitting transducer was driven with three cycles for 47 and 52 kHz and five cycles for 75 and 87 kHz produced from a signal generator, and the waveform was received by the receiving transducer and was recorded by a digital recorder at sample rate of 10 MHz. Figure 3 shows the example waveform and frequency spectrum recorded for one core at 75 kHz. The sound speed and attenuation were measured under the conditions of the atmospheric pressure and the temperature range of 19.2–19.8 °C. The sound speed $V_p$ was calculated using the length of sediment core and travel time of acoustic signal through the sediment core. Before measuring the attenuation, the sediment cores were cut into two sections with different lengths. We selected four sediment cores to measure the attenuation at 52 and 87 kHz, as these four sediment cores had enough lengths to be cut into two sections. The attenuation $\alpha_p$ was calculated using the base-10 logarithm of the ratio of peak magnitude of received signals and the difference in the length of sediment cores. The calculation equations of sound speed and attenuation were listed as

$$V_p = \frac{\Delta l}{\Delta t} = \frac{l_1 - l_2}{t_1 - t_2}$$  \hspace{1cm} (8)

$$\alpha_p = \frac{20}{\Delta l} \log_{10} \left( \frac{A_{p1}}{A_{p2}} \right)$$  \hspace{1cm} (9)

where $l_1$ and $l_2$ was the length of two sections of the sediment cores; $t_1$ and $t_2$ was the travel time of acoustic signal through them; and $A_{p1}$ and $A_{p2}$ was the first three cycles or five cycles magnitude of received signals in sediment cores before and after cut off. Using the calculation equation reported in Medwin (1975), the sound speed of seawater with laboratory environment temperature can be calculated. Thus, the laboratory sound speed ratio VR can be obtained as the ratio of the sediment sound speed $V_p$ to the water sound speed $V_w$.

### 2.3. Sediments Physical Properties Measurement

The physical properties of sediments, including wet bulk density, porosity, grain size fraction, and mean grain size were measured in laboratory. All the physical properties were measured under the conditions of
the atmospheric pressure and the temperature range of 25.1–25.6 °C. The wet bulk density was calculated from the weight and the volume measured using a steel ring sampler (6 cm in diameter and 2 cm in height). The porosity of sediment sample was calculated by the grain density, wet bulk density, and water content. The grain size fraction was measured using the combined sieving and densimeter settling method. Graphic method was used in sediment classification. After plotting the grain size cumulative distributions, mean grain sizes were determined by averaging the d16, d50, and d84 percentiles, median grain sizes were set as d50. Mean grain size $M_z$ and median grain size $M_d$ is presented in $\phi$ units ($\phi = -\log_2 u_g$, where $u_g$ is grain diameter in millimeter).

### 3. Data

#### 3.1. The Physical Properties of Sediments

The grain size distributions obtained using combined sieving and densimeter settling method are plotted in Figure 4, and the grain size data were averaged from all the sediment cores. The sediment has a distribution with 64% of the grain sizes being between 0.1 and 0.4 mm (1.3 $\phi$ to 3.3 $\phi$), and with 28% of the measured grain sizes being below 0.01 mm (6.64 $\phi$). Most of the grains are the medium to very fine sand using Udden-Wentworth sediment grain size classes. The mean grain size of sediment is 0.042 mm (4.59 $\phi$), and the median grain size of sediment is 0.143 mm (2.80 $\phi$). The sediments are characterized as 67.4% sand content, 10.4% silt content, and 22.2% clay content. The measured physical properties of each sediment core were listed in Table 1 in detail.

The measured wet bulk density of sediments $\rho_s$ is 1.86–1.96 g/cm³ with an average value of 1.90 g/cm³. The measured grain bulk density of sediments $\rho_g$ is 2.71–2.73 g/cm³ with an average value of 2.72 g/cm³. The water content $w$ is 27.7%–39.0% with an average value of 32.8%. With the measured wet bulk density, the grain bulk density, and the water content, the porosity $n$ can be calculated using the follow equation,

$$n = 1 - \frac{\rho_s}{\rho_g}$$

In this study, the porosity is 0.43–0.51 with an average of 0.47. Bachman (1985) and Orsi and Dunn (1991) have considered that the coarser sediments have smaller porosity than that of fine-grained sediments, while a sediment of a given grain size may have a wide range of porosity. As the sediment grain is not spherical particle with uniform diameter, the porosity of sediment is related to the particle-size distribution and the shape of the grains. Bachman (1985) and Orsi and Dunn (1991) have provided the regression equations between porosity $n$ and mean grain size $M_z$.

### Table 1

**The Measured Physical Properties of Sediments**

| Wet bulk density g/cm³ | Porosity | Water content % | Gravel content % | Sand content % | Silt content % | Clay content % | Mean grain size in $\phi$ | Median grain size in $\phi$ |
|------------------------|----------|-----------------|------------------|----------------|----------------|----------------|------------------------|--------------------------|
| T1                     | 1.87     | 0.51            | 38.2             | 0.0            | 60.9           | 10.5           | 28.6                   | 4.98                     | 3.21                     |
| T2                     | 1.92     | 0.46            | 30.4             | 0.0            | 63.2           | 12.5           | 24.3                   | 4.97                     | 3.24                     |
| T3                     | 1.88     | 0.48            | 34.0             | 0.0            | 72.4           | 8.7            | 18.9                   | 4.61                     | 2.82                     |
| T4                     | 1.90     | 0.48            | 33.6             | 0.0            | 60.7           | 9.7            | 29.6                   | 5.03                     | 3.26                     |
| T5                     | 1.87     | 0.51            | 39.0             | 0.0            | 64.5           | 10.6           | 24.9                   | 4.79                     | 3.01                     |
| T6                     | 1.96     | 0.43            | 27.7             | 3.5            | 71.7           | 5.1            | 19.7                   | 4.33                     | 2.26                     |
| T7                     | 1.86     | 0.49            | 34.9             | 0.0            | 73.6           | 9.6            | 16.8                   | 4.08                     | 2.29                     |
| T8                     | 1.94     | 0.45            | 30.6             | 0.0            | 61.0           | 14.7           | 24.3                   | 4.76                     | 3.03                     |
where \( n \) is porosity, \( M_z \) is the mean grain size in \( \phi \). The variation of porosity with grain size was illustrated in Figure 5, including the model of equations (A11) and (A12) and measured data. The measured data provided a more consistent variation with equation (A12) than equation (A11), and most of the measured data were not even in the 70% confidence limits of equation (A11). Although Hamilton and Bachman (1982) established their regression equation between porosity and mean grain size, they considered that there are significant differences in the porosity in different environment given the same mean grain size. Hamilton and Bachman (1982) and Orsi and Dunn (1991) think that the different equations were probably related to grain shape, grain sorting, mineralogy, sediment microstructure, etc. The clay mineralogical differences were important factor that influence the water content and porosity of sediments, especially the montmorillonite content, which can adsorb more water to increase the water content and the porosity of sediments. Rateev et al. (1968) has reported that the montmorillonite content of sediments was 40%−60% in Pacific Ocean, where Hamilton's equations were established. The montmorillonite content was about 3% in East China Sea shelf (Wang et al., 2015), which is close to the data 0%−10% in Orsi and Dunn (1991). Thus, the measured data accord better with the equation (A12) than equation (A11).

3.2. The Acoustic Properties of Sediments

The measured sound speed ratio and attenuation are listed in Table 2. The in situ sound speeds of sediments measured at 30 kHz using BISAMS were 1,568.81−1,627.29 m/s with an average value of 1,598.25 m/s, the in situ attenuation of sediments were 4.16−11.08 dB/m with an average value of 7.03 dB/m. The in situ sound speed ratios of sediments were 1.03−1.07 with an average value of 1.05. As shown in Figure 6, most of the laboratory sound speed ratios at 47 kHz accord well with the in situ sound speed ratios at 30 kHz, with the exception of a few higher laboratory data.

Jackson and Richardson (2007) established the regression equations of the in situ sound speed ratio \( VR \) versus the wet bulk density \( \rho \), the porosity \( n \), the mean grain size \( M_z \), respectively,

\[
V_{\rho}R = 1.705 - 1.035\rho + 0.3664\rho^2 \tag{13}
\]

\[
V_{n}R = 1.576 - 1.5677n + 1.0269n^2 \tag{14}
\]

Table 2

|           | In situ sound speed m/s | In situ sound speed ratio | Laboratory sound speed ratio | In situ attenuation dB/m | Laboratory attenuation dB/m |
|-----------|-------------------------|---------------------------|----------------------------|--------------------------|-----------------------------|
|           | 47 kHz                  | 52 kHz                    | 75 kHz                     | 87 kHz                   | 52 kHz                      | 87 kHz                      |
| T1        | 1,568.81                | 1.030                     | 1.035                      | 1.035                    | 1.046                       | 4.16                        | 22.54                       | 36.36                       |
| T2        | 1,605.74                | 1.053                     | 1.051                      | 1.052                    | 1.064                       | 1.062                       | 6.85                        | 28.77                       | 46.72                       |
| T3        | 1,612.06                | 1.061                     | 1.065                      | 1.060                    | 1.071                       | 1.070                       | 7.72                        | -                           | -                           |
| T4        | 1,591.12                | 1.043                     | 1.036                      | 1.044                    | 1.049                       | 1.053                       | 7.31                        | -                           | -                           |
| T5        | 1,591.12                | 1.043                     | 1.030                      | 1.043                    | 1.049                       | 1.050                       | 7.31                        | -                           | -                           |
| T6        | 1,627.29                | 1.065                     | 1.082                      | 1.076                    | 1.095                       | 1.089                       | 11.08                       | 27.68                       | 42.23                       |
| T7        | 1,593.57                | 1.042                     | 1.062                      | 1.058                    | 1.069                       | 1.066                       | 4.19                        | -                           | -                           |
| T8        | 1,596.26                | 1.045                     | 1.072                      | 1.076                    | 1.082                       | 1.087                       | 7.59                        | 15.08                       | 33.69                       |
| Average Value | 1,598.25                | 1.048                     | 1.054                      | 1.056                    | 1.066                       | 1.068                       | 7.03                        | 23.52                       | 39.75                       |
Jackson and Richardson (2007) also established the regression equations of the in situ attenuation factor $k$ versus the wet bulk density $\rho$, the porosity $n$, the mean grain size $Mz$, respectively,

$$k = 0.00332e^{2.41\rho}$$  

$$k = 2.153e^{-4.01n}$$  

$$k = 0.697e^{-0.183Mz}$$  

The measured sound speed ratio and attenuation factor in this study were compared with above regression equations’ curves, as shown in Figures 7a–7c and 8a–8c, respectively. The comparison results indicated that the measured sound speed ratios can accord well with the empirical curves fitting based on data measured at higher frequency of 38 or 58 kHz, although the measured data were slightly lower than the curves, which may be due to sound speed dispersion predicted by poroelastic theory (Jackson & Richardson, 2007). As shown in Figure 8, the measured attenuation factors also can accord with the empirical curves, but two data points were below the lines and one data point was above the lines. The determination coefficients of regression equations versus physical properties for attenuation factor were low (the value range of $r^2$ was 0.45–0.52), and Jackson and Richardson (2007) has pointed out that these equations should be used with caution and the measured data are much preferred.

$V_{MzR} = 1.190 - 0.03956Mz + 1.9476 \times 10^{-3}Mz^2$  

**Figure 6.** Comparisons of the in situ sound speed ratios of sediments at 30 kHz versus the laboratory sound speed ratios at 47 kHz.

**Figure 7.** Sound speed ratio as a function of wet bulk density (a), porosity (b), and mean grain size (c). The solid black points represent the measured data in this study, and the solid black lines represent the empirical equations (13), (14), and (15), respectively.
4. Results and Discussions

The sound speed ratio derived from the in situ data and laboratory data were plotted against frequency in Figure 9. The attenuation derived from in situ data and laboratory data was plotted against frequency in Figure 10. The individual black points at each frequency represent the measured values of sound speed ratio and attenuation at the eight locations. The in situ data were averaged with three data points at each location using the data from the three received transducers. The open points at each frequency represent the mean value of the measurement data at the eight locations. In the band of 30–87 kHz, sound speed ratios from all locations have overall variation of 0.03 at 30, 52, and 87 kHz, and 0.05 at 47 and 75 kHz. The attenuation from four locations have obvious variation of 6.92 dB/m at 30 kHz, 13.69 dB/m at 52 kHz, and 13.03 dB/m at 87 kHz. An increase in sound speed ratio with frequency was clearly evident. The dashed line in Figure 9 representing the frequency dependence in the plot is an empirical fit to the data given by

\[ VR = 1.0359 + 0.0004f \quad (30 \text{ kHz} < f < 90 \text{ kHz}) \]  

where \( VR \) is the sound speed ratio, \( f \) is the frequency in kilohertz. The correlation coefficient of equation (19) is about 0.98. The curve for sound speed ratio has a similar regular expression with the fitting result in Hines et al. (2010). As shown in Figure 10, an increase in attenuation with frequency also was clear evident. The frequency dependence of attenuation was fitted expressing as a dashed line in Figure 10. The empirical fit was given by
\( \alpha = 0.03 f^{0.63} (30 \text{ kHz} < f < 90 \text{ kHz}) \)  

(20)

where \( \alpha \) is the attenuation in dB/m and \( f \) is the frequency in kilohertz. The correlation coefficient of equation (20) is about 0.96. The attenuation increases nonlinearly in the band of 30–87 kHz and seems to be proportional to \( f^{0.63} \) dependence, which is different to the \( f^1 \) dependence in Hamilton (1980), the \( f^{0.5} \) dependence in Biot theory, and the \( f^2 \) dependence in Sessarego et al. (2008).

Marine sediments can be regarded as a fluid-filled porous medium and the acoustic wave propagation in sediments can be physically modeled by Biot-Stoll model. In the Biot theory, acoustic wave attenuation is primarily attributed to the viscous losses due to relative motion between the pore fluid and the skeletal frame. The Biot-Stoll model predictions for values of the sound speed ratio and the attenuation were plotted in Figures 11a–11b. The dashed points in Figures 11a and 11b represent the averaged data from Figures 9, 10, plotted as a function of frequency. The vertical bars on the data represent the variation range of the measured data at different sites.

The lines in Figure 11 represented the Biot-Stoll model prediction using different input physical parameters calculated by different porosity and mean grain size, obtained from the measurements range of sediments. The input parameters were listed in Table 3. The red dotted line and solid line represent the model predictions using the maximum mean grain size of 4.08 and the minimum mean grain size of 5.03, when chosen the porosity with a maximum value of 0.51. The blue dotted line and solid line represent the model predictions using the maximum mean grain size of 4.08 and the minimum mean grain size of 5.03, when chosen the porosity with a minimum value of 0.43. The black solid line represents the model predictions using the average values of porosity and mean grain size of all eight sites sediments. The model predictions were evaluated using the parameters estimated from the literature or calculated with the extended equations by Schock (2004). The grain bulk modulus, the fluid dynamic viscosity, the fluid density, the fluid bulk modulus, the bulk dissipation factor, and the shear dissipation factor were estimated from the literature (Williams et al., 2002). The permeability, the pore size, the tortuosity, the frame shear modulus, and the frame bulk modulus were calculated using the equations introduced in Schock (2004). According to the physical relationship of Kozeny-Carman (Holland & Brunson, 1988), the permeability \( \kappa \) in m² can be approximated by

\[
\kappa = \frac{1}{K'S_0} \frac{n^3}{(1-n)^3} 
\]

(21)

where \( S_0 \) is the specific surface of the particles in the sediment in m⁻¹ and can be defined as \( S_0 = 6/\bar{u}_g \), where \( \bar{u}_g \) is the mean grain diameter in meters shown in Table 3. \( K' \) is an empirical constant approximately equal to 5, and \( n \) is the porosity. However, the Kozeny-Carman equation is accurate only for specific cases such as unconsolidated well-sorted sediments with rounded grains (Hovem & Ingram, 1979). In consideration of the unknown influence factors of the pore geometry, there is no simple equation to estimate permeability from mean grain size and porosity. Schock (2004) established the error introduced by equation (22) in calculating permeability, assumed that the equation (22) overestimates the
permeability on the average by a factor of \( \sqrt{10} \) and extended the equation as

\[
\kappa = \frac{u_g^2}{180 (1-n)} \frac{1}{\sqrt{10}}
\]  
(22)

The tortuosity \( \alpha \) can be calculated following Stoll (1977)

\[
\alpha = \begin{cases} 
1.35 & \phi \leq 4 \\
-0.3 + 0.4125\phi & 4 < \phi < 8 \\
3.0 & \phi \geq 8 
\end{cases}
\]

(23)

where \( \phi \) is the mean grain size and is dimensionless, \( \phi = -\log_2 u_g \), where \( u_g \) is the mean grain diameter in millimeters.

Hovem and Ingram (1979) established an equation developed using the hydraulic radius concept for uniform spherical grains to calculate the pore radius. To consider the estimate error, Schock (2004) provided a factor of \( \sqrt{10} \) for the equation overestimates the pore radius, and extended the equation to calculate the pore size \( a \) in meters as

\[
a = \frac{u_g n}{3 (1-n)} \frac{1}{1.8}
\]

(24)

Returning to Figure 11a, the trends of the measured sound speed ratio are similar to the Biot-Stoll model predictions. The magnitude ranges of sound speed ratio are in the upper limit and the lower limit curves. The mean values of sound speed ratio at each frequency accord with the prediction curve using the mean value of measured porosity and measured mean grain size. The mean difference in sound speed between the curve estimates is about 3% using the different porosity and the same mean grain size or using the same porosity and the different mean grain size. The qualitative agreement in the frequency trend of the measured sound speed ratio and the Biot-Stoll model prediction indicates that the model can predict the sound speed well using the input parameters calculated by above equations. The comparison results also indicate that the fit of

Table 3
The Values of Biot-Stoll Model Input Parameters for Different Porosity and Mean Grain Size

| Physical Parameter              | Symbol | Unit       | \( n = 0.51 \) | \( M_z = 5.03 \) (in \( \phi \)) | \( n = 0.51 \) | \( M_z = 4.08 \) (in \( \phi \)) | \( n = 0.43 \) | \( M_z = 5.03 \) (in \( \phi \)) | \( n = 0.43 \) | \( M_z = 4.08 \) (in \( \phi \)) | \( n = 0.47 \) | \( M_z = 4.59 \) (in \( \phi \)) |
|---------------------------------|--------|------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|
| Grain Bulk Modulus*            | \( K_g \) | Pa         | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) | \( 3.2 \times 10^{10} \) |
| Fluid Dynamic Viscosity*       | \( \eta \) | kg m\(^{-1}\) s\(^{-1}\) | 0.00105 | 0.00105 | 0.00105 | 0.00105 | 0.00105 | 0.00105 | 0.00105 | 0.00105 |
| Grain Density                  | \( \rho_g \) | kg/m\(^3\) | 2.650 | 2.650 | 2.650 | 2.650 | 2.650 | 2.650 | 2.650 | 2.650 |
| Fluid Density*                 | \( \rho_f \) | kg/m\(^3\) | 1.023 | 1.023 | 1.023 | 1.023 | 1.023 | 1.023 | 1.023 | 1.023 |
| Fluid Bulk Modulus*            | \( K_f \) | Pa         | \( 2.38 \times 10^{9} \) | \( 2.38 \times 10^{9} \) | \( 2.38 \times 10^{9} \) | \( 2.38 \times 10^{9} \) | \( 2.38 \times 10^{9} \) | \( 2.38 \times 10^{9} \) | \( 2.38 \times 10^{9} \) |
| Permeability+                  | \( \kappa \) | m\(^{-2}\) | \( 9.33 \times 10^{-13} \) | \( 3.38 \times 10^{-12} \) | \( 4.31 \times 10^{-13} \) | \( 1.56 \times 10^{-12} \) | \( 1.19 \times 10^{-12} \) | \( 1.19 \times 10^{-12} \) | \( 1.19 \times 10^{-12} \) |
| Tortuosity+                    | \( \alpha \) | —          | 1.77 | 1.38 | 1.77 | 1.38 | 1.38 | 1.59 | 1.59 | 1.59 |
| Pore Size+                     | \( a \) | m          | \( 5.97 \times 10^{-6} \) | \( 1.14 \times 10^{-5} \) | \( 4.41 \times 10^{-6} \) | \( 8.38 \times 10^{-6} \) | \( 7.01 \times 10^{-6} \) | \( 7.01 \times 10^{-6} \) | \( 7.01 \times 10^{-6} \) |
| Frame Shear Modulus*           | \( \mu \) | Pa         | \( (0.895-i0.18) \times 10^{7} \) | \( (0.895-i0.18) \times 10^{7} \) | \( (1.355-i0.18) \times 10^{7} \) | \( (1.355-i0.18) \times 10^{7} \) | \( (1.09-i0.18) \times 10^{7} \) | \( (1.09-i0.18) \times 10^{7} \) | \( (1.09-i0.18) \times 10^{7} \) |
| Frame Bulk Modulus*            | \( K_b \) | Pa         | \( (1.20-i0.24) \times 10^{7} \) | \( (0.995-i0.20) \times 10^{7} \) | \( (1.818-i0.24) \times 10^{7} \) | \( (1.506-i0.20) \times 10^{7} \) | \( (1.33-i0.22) \times 10^{7} \) | \( (1.33-i0.22) \times 10^{7} \) | \( (1.33-i0.22) \times 10^{7} \) |
| Bulk Dissipation Factor*       | \( \delta_k \) | —          | 0.0225 | 0.0225 | 0.0225 | 0.0225 | 0.0225 | 0.0225 | 0.0225 | 0.0225 |
| Shear Dissipation Factor*      | \( \delta_\mu \) | —          | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |

Note: The symbol (*) indicates estimated parameters from the literature. The symbol (+) indicates calculated parameter using measured parameters.
the measured data to the model curves can be improved by varying the input parameters inside the range of the measurements shown in Table 1, especially by averaging the porosity and the mean grain size value in the sampling local region.

As shown in Figure 11b, the model prediction curves plotted using different porosity and different mean grain size are largely different. Additionally, when the frequency is below 70 kHz, the attenuation predicted using coarser grains \( (M_z = 4.08) \) is higher than that predicted using finer grains \( (M_z = 5.03) \), and the attenuation predicted using porosity with a value of 0.51 is higher than that predicted using porosity with a value of 0.43. When the frequency is above 70 kHz, the attenuation predicted using coarser grains \( (M_z = 4.08) \) is lower than that predicted using finer grains \( (M_z = 5.03) \), and the attenuation predicted using porosity with a value of 0.51 is lower than that predicted using porosity with a value of 0.43. The measured attenuation data run essentially parallel to, but below, the Biot-Stoll model fits when the sound speed data get a good fit, which is different to the result in Zimmer et al. (2010). The attenuation data show a steeper trend than the Biot-Stoll model curve trend when the sound speed data get a good fit, which is similar to the result in Nosal et al. (2008) and in Zimmer et al. (2010). We tried to get a best model-data fit by varying the input parameters in the calculated data range as shown in Table 3. When the permeability changed to \( 4.31 \times 10^{-13} \) m\(^2\), the porosity changed to 0.44, the tortuosity changed to 1.77, and the pore size changed to \( 5.95 \times 10^{-6} \) m, the sound speed and attenuation get best fit to the model curves simultaneously (Figure 12). By the equations (equations (22)–(24)), we can calculate the effective grain size, and the correction factors in equations (22) and (24). The calculation results were presented as follows: the effective grain size was 5.02, the correction factor in equation (22) was \( \sqrt{11} \) and the correction factor in equation (24) was 1.35. Thus, the calculation equations for permeability and for pore size can be expressed as

\[
x = \frac{u_s^2}{180} \frac{n^3}{(1-n)^2} \frac{1}{\sqrt{11}} \quad (25)
\]

\[
a = \frac{u_s}{3} \frac{n}{1-n} 1.35 \quad (26)
\]

The detailed comparisons of the attenuation prediction curves from the literature were plotted in Figure 13. Among these model curves, the black line represents the model predictions using the parameters in Table 3, the blue lines represent the Biot-Stoll model or Buckingham model predictions from several measurements, and the red lines represent the fit curves in different frequency range from several measurements. The prediction lines for 1999 Sediment Acoustics Experiment from Williams et al. (2002) and Buckingham (2005), and the fit lines from Zhou et al. (2009) and from Yang and Tang (2017) represent the attenuation in coarse sandy sediments. The prediction line from Kimura (2011) represents the attenuation in fine sandy sediments \( (M_z = 3.90) \) from 80–140 to 300–700 kHz. The fit line from Ballard et al. (2014) represents the attenuation in muddy sediments from 60 to 110 kHz. From Figure 13, we found that there are some differences between these curves, which due to the different sediments. The Biot-Stoll model prediction curve in this study is more similar to the Kimura’s curve than Williams’s curve, just as the sediments have close porosity and grain size in this study and in Kimura (2011). Additionally, these three curves also present the similar trend that the coarser sediments have larger attenuation in the low frequency range, while the fine sandy sediments have larger attenuation in the high frequency range than the coarse sandy sediments and the muddy sediments. These results are similar to the conclusions in Hamilton (1980), which reported the higher attenuation in sediments with mean grain size of 3 \( \phi \) – 5\( \phi \). Among these fit curves, Ballard’s curve for muddy sediments is closer to the model prediction curve in this study, while Zhou’s and Yang and Tang’s curves are between the curve in this study and Williams’s curve. Compared to the model prediction curves, these fit curves could not predict attenuation in broadband frequency. The high frequency acoustic properties and the middle-low frequency properties for different types of sediments were rarely measured together.

![Figure 13. Comparisons of several model prediction curves and fit lines for the attenuation to the model prediction curve in this study.](image-url)
Therefore, subsequent work can try to provide the broadband attenuation fit curve for sediments with different size fractions through summarizing a set of measurement data.

5. Conclusions

This study collected the acoustic data in fine sandy sediments using both in situ method and laboratory method. The relations of sound speed ratio and attenuation against physical properties were found to accord well with several regression correlations from the literature. The relation between porosity and mean grain size also was found in the prediction confidence interval of some empirical equations. Above knowledge reveals that the acoustic data in this study are credible and can support the analysis on the frequency dependence of acoustic properties.

This study presented the frequency dependence of the sound speed and attenuation across the frequency band of 30–87 kHz. The sound speed ratio increases from 1.048 to 1.068 demonstrating a dispersion of 0.02 (~30 m/s), and the attenuation increases from 7.03 to 39.75 dB/m. According to calculating the model input parameters, including permeability and the pore size using Schock’s extended equations, the Biot-Stoll model predictions were established. The frequency dependence of sound speed ratio is in good agreement with model prediction, while the attenuation is slightly below the prediction curve. The attenuation was more consistent with the result reported for the fine sediments than that for the coarse sandy sediments. It should be noted that the fine sandy sediments may have larger attenuation than that the coarse sediments at high frequencies, while the coarse sediments show higher attenuation at low frequencies. Further study of sediments with different grain sizes at both low frequency and high frequency is recommended and to verify the different attenuation properties at different frequency band.

Appendix A

As a poroelastic theory, Biot theory can explain the propagation characteristics of acoustic wave in the porous fluid-saturated medium. The seafloor sediments are usually composed of solid particles and pore fluid, and the acoustic properties of granular water-saturated sediments can be predicted by the Biot-Stoll model. Biot theory developed a pair of coupled differential equations with permeability $\kappa$, pore fluid viscosity $\eta$, bulk density $\rho$, and fluid density $\rho_f$.

\[
\nabla^2 (H\varepsilon - C\zeta) = \frac{\partial^2}{\partial t^2} \left( \rho\varepsilon - \rho_f\zeta \right) \tag{A1}
\]

\[
\nabla^2 (C\varepsilon - M\zeta) = \frac{\partial^2}{\partial t^2} \left( \rho_f\varepsilon - m\zeta \right) - \frac{\eta}{\rho_f} \frac{\partial \zeta}{\partial t} \tag{A2}
\]

where $\zeta$ is the incremental volume of fluid that enters or leaves the frame and $\varepsilon$ is volumetric strain of the frame. The four moduli, $H$, $M$, $C$ and $D$, can be related to parameters of the constituent media following these relationships:

\[
H = \frac{(K_g - K_f)^2}{D - K_f} + K_f + \frac{4\mu}{3} \tag{A3}
\]

\[
C = \frac{K_g (K_g - K_f)}{D - K_f} \tag{A4}
\]

\[
M = K_g \frac{K_f}{D - K_f} \tag{A5}
\]

\[
D = K_g \left( 1 + \frac{\beta K_g}{K_w - 1} \right) \tag{A6}
\]

where $\mu$ is the frame shear modulus, $\beta$ is the porosity, $K_g$ is the bulk modulus of the individual sediment grains, $K_w$ is the bulk modulus of the pore water, and $K_f$ is the bulk modulus of the frame. $K_g$ and $K_w$ are usually taken to be real, while the frame bulk modulus $K_f$ and frame shear modulus $\mu$ are usually
assumed to be complex, which can account for a portion of the loss in a porous medium. Stoll developed the following expression for a harmonic plane wave traveling through a porous medium, $F$ is a viscosity correction to account for frequency-dependent viscous losses of the oscillating fluid in the sediment pores.

\[
\begin{vmatrix}
Hk^2 - \rho \omega^2 & \rho_f \omega^2 - CK^2 \\
CK^2 - \rho_f \omega^2 & m\omega^2 - MK^2 - \frac{\omega F\eta}{\kappa}
\end{vmatrix} = 0
\]  

(A7)

Thus, the solution of complex wave number $k$ has the form

\[
k_q = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}
\]  

(A8)

where the $+$ sign provides $k_q$ for the fast wave ($q = 1$) and the $-$ sign provides $k_q$ for the slow wave ($q = 2$). In this equation, $a$, $b$, and $c$ can be expressed as follows:

\[
a = C^2 - HM
\]  

(A9)

\[
b = \left( Hm + \rho M - 2\rho_f C \right) \omega^2 + i \frac{F \eta H}{\kappa} \omega
\]  

(A10)

\[
c = \left( \rho_f^2 - \rho_m \right) \omega^4 - i \frac{F \eta \rho \omega^3}{\kappa}
\]  

(A11)

\[
m = \frac{\alpha \rho_f}{n}
\]  

(A12)

where $\alpha$ is the tortuosity and $\omega$ is the angular frequency of acoustic wave. The density of sediments $\rho$ can be expressed as

\[
\rho = \rho_g \tau + (1-\tau) \rho_e
\]  

(A13)

where $\rho_e$ is the mass density of grains. The sound speed can be expressed as

\[
V_p = \frac{\omega}{Re[k_1]}
\]  

(A14)

The attenuation can be expressed as

\[
\alpha_p = -Im[k_1]
\]  

(A15)

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