

Acoustic properties and their frequency dependence in fine-grained sediments: a geoacoustic probe experiment*

Qingfeng HUA^{1,2}, Yongqi LIN^{1,2}, Xiangmei MENG^{1,2}, Jingqiang WANG^{1,2}, Lei SUN^{1,2},
Guanbao LI^{1,2,**}

¹Key Laboratory of Marine Geology and Metallogeny, First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China

²Laboratory of Marine Geology, Laoshan Laboratory, Qingdao 266061, China

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Abstract The acoustic properties of fine-grained sediments have recently attracted increasing attention from the scientific community. Understanding the relationships between these properties and frequency is crucial for advancing the fundamental theory of sediment acoustics and its practical applications. An in-situ acoustic measurement system, namely, the geoacoustic probe, was developed for determining the broadband acoustic properties of seafloor sediment, and an experiment was conducted in the muddy area of the Zhujiang (Pearl) River estuary in Guangdong, South China. To calibrate the geoacoustic probe, measurements were made with a sound speed profiler in near-bottom seawater for comparison. In-situ measurements were subsequently performed at 28 frequencies ranging 5–200 kHz in clayey silt sediment. The speed of sound ratio and attenuation were calculated using interreceiver correlation and linear fitting methods. The calculated speeds of sound ratios were consistently lower than 1 and generally linearly increased with increasing frequency. In contrast, the attenuation in fine-grained sediment was less than that in sandy sediment, with an increase in $f^{1.36}$ dependence with increasing frequency. The measured acoustic properties approached those based on viscous grain shearing theory, revealing suitable agreement with the predicted values, except for a few attenuation measurements at the end of the frequency band.

Keyword: speed of sound; attenuation; fine-grained sediment; in-situ measurement; modeling

1 INTRODUCTION

The acoustic properties of the seabed, mainly the speed of sound and attenuation, are of notable interest to marine acousticians, geophysicists, and ocean engineers. The accurate measurement of these parameters is necessary for modeling underwater sound propagation. Over the past two decades, researchers have focused on studying the frequency dependence of the acoustic properties of seafloor sediment. Seafloor sediments are typically classified into different types in grain size composition, and each type of sediment exhibits various acoustic properties and frequency dispersion (Hamilton, 1970, 1980). Several experiments, including those involving SAX99, SAX04, SW06, TREX13, and SBCEX2017, have been conducted with the support

of numerous novel measurement techniques (Thorsos et al., 2001; Sessarego et al., 2008; Turgut and Yamamoto, 2008; Yang and Tang, 2017; Wilson et al., 2020). In these experiments, in-situ acoustic measurements have played a crucial role in providing important information on the frequency dispersion of acoustic properties (Williams et al., 2002; Hines et al., 2010; Yang and Tang, 2017). These experiments were conducted across a range of frequencies from a few hundred hertz to a few hundred kilohertz to study the frequency dependencies of speed of sound and attenuation for different sediment types, especially in sandy

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** Corresponding author: gbli@fio.org.cn

sediments, and the existence of acoustic dispersion is generally accepted, although there is still ongoing debate regarding the theoretical models for this dispersion (Buckingham, 2005; Zhou et al., 2009; Chotiros, 2017).

In contrast, the acoustic characteristics of fine-grained sediment have not been extensively studied and are poorly understood. Field acoustic measurements in silty and muddy sediment have been limited in the past, as have model comparisons (e.g., Orsi and Dunn, 1990; Hou et al., 2018; Ballard et al., 2020). To assess the adaptability of theoretical models for the acoustic properties of seafloor sediments, the acoustic measurement and modeling of fine-grained sediments have become research hotspots in recent years (Ballard et al., 2020; Yang and Jackson, 2020). Through in-situ measurements and sediment core recovery and testing, researchers have discovered that the speed of sound of fine-grained sediment is generally lower than that of seawater under the same temperature and pressure conditions (Hamilton, 1956; Orsi and Dunn, 1990; Holland and Dosso, 2013; Li et al., 2020). Additionally, the attenuation of fine-grained sediment is typically the weakest among those of all sediment types (Hamilton, 1972). Many studies have demonstrated the difficulty in accurately measuring attenuation records in fine-grained sediments. This challenge arises from the voltage response of the transducer when it transmits signals in seawater versus sediments (Yang and Tang, 2017). Several pioneering studies have focused on investigating the frequency dispersion in fine-grained sediment. Siegmann and Pierce (2015) reviewed research on the acoustic properties of mud and concluded that the frequency dependency observed in sandy sediment cannot be applied to mud. Based on laboratory P-wave and microstructure measurement for reconstituted muddy sediment, the card-house theory and viscous grain shear theory were examined by Ballard et al. (Ballard et al., 2014; Ballard and Lee, 2016) to fit the dispersion of the measured speed of sound and attenuation. Wang et al. (2022) and Kan et al. (2018) demonstrated the differences in the speed of sound and its dispersion between fine-grained silty clay and other sediment types. Zhou et al. (2024) reported sound attenuation in the 13–5 000-Hz range based on geoacoustic inversion, which showed an almost linear relationship with frequency and well fit the viscous grain-shearing (VGS) theory. In addition to these sporadic reports, an international,

multidisciplinary, and multi-institutional research project called the Seabed Characterization Experiment (SBCEX) was conducted at the New England Mud Patch (NEMP) site offshore of Massachusetts, USA in 2017. The aim of this project was to understand the physical mechanism of sound propagation in muddy sediment and its influence on the acoustic field. Comprehensive methods, including core testing, in situ measurements, and geoacoustic inversion, were used to determine the frequency and depth dependence of the acoustic properties. Low dispersion was observed (Wilson et al., 2020, 2022). However, owing to the various measurement methods used to cover a broad frequency bandwidth, the results were significantly scattered, which reduced the credibility of the conclusions regarding frequency dispersion. Furthermore, the sediment in the NEMP was impure muddy sediment with many sand inclusions (Wilson et al., 2020; Chaytor et al., 2022). Characterizing both the speed of sound and attenuation synchronously using a theoretical model poses a greater challenge. Further efforts are needed to measure the acoustic attenuation more precisely by broadband in situ instruments and clarify the dispersion characteristics of the acoustic properties in fine-grained sediment. In fact, fine-grained sediments not only constitute a significant portion of deep-sea deposits but are also widely distributed offshore in the world. Their acoustic properties, including speed of sound and attenuation vertical gradients due to compaction, are obviously meaningful for sound propagation studies in the ocean and for subbottom profile exploration. Therefore, understanding their acoustic properties is crucial for marine acoustic-related studies and applications, just as it is for sandy sediment.

Overall, previous studies, especially those based on VGS theory, have aimed to primarily measure geoacoustic parameters in fine-grained sediments, and tentative model-based data fitting efforts have been made. These data were generally acquired within a limited range or as a mixture of results from different measurement techniques, making model fitting difficult. For this reason, we developed a broadband (5–200 kHz) in-situ geoacoustic measurement system (the geoacoustic probe) and performed an in-situ experiment to measure the speed of sound and attenuation in fine-grained sediments. Herein, the experimental results are presented, the frequency dependence of the acoustic properties analyzed, and the fitting to VGS theory discussed.

2 MATERIAL AND METHOD

2.1 Environment

The experimental site chosen for this study occurs near Aizhou Island in the Wanshan Archipelago, which is located off the Zhujiang (Pearl) River estuary in Guangdong, South China (Fig.1). The site is approximately 3 km northeast of the island in water depth of approximately 20 m. The hydrodynamics in this area are relatively weak because of the island barrier, resulting in the deposition of fine-grained material transported from the river. The sediment found at this site is classified as clayey silt, with silt being the predominant component, accounting for an average of 64.90% of the sediment composition. Clay is the second most abundant component, with an average content of 25.81%, while sand constitutes less than 10% of the total sediment. The mean grain size of this sediment type ranges from 5.54ϕ to 8.14ϕ , on average of 6.77ϕ (Shi, 2014). Clayey silt is widely distributed along the coast of Guangdong to the west of Zhujiang River estuary and is located mainly on the inland shelf at water depths less than 50 m. The sedimentary materials in this region originate from terrigenous clastics transported in Zhujiang River system, and the deposition process is influenced by the coastal current flowing in the southwest direction. High-resolution chirp profiling and coring were used to study a Holocene mud area derived from Zhujiang River. The area is elongated, spanning approximately 400 km, with a maximum

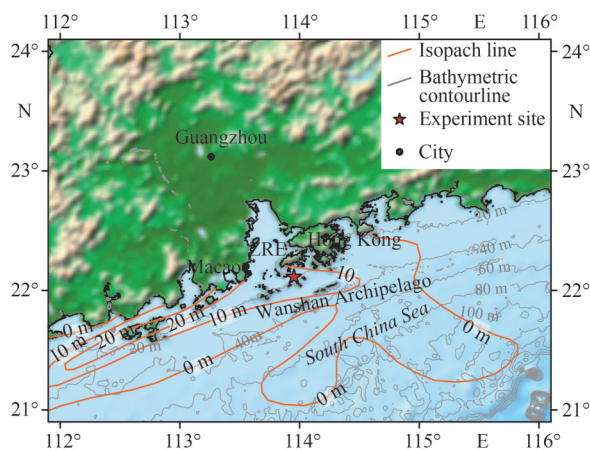


Fig.1 Location of the experimental site

The orange lines indicate the isopach (m) distribution of the Holocene-aged Zhujiang (Pearl) River-derived sediment, according to Ge et al. (2014). The bathymetric data comes from the General Bathymetric Chart of the Oceans (GEBCO, Compilation Group, 2025). ZRE: Zhujiang (Pearl) River estuary.

depth above 20 m. It extends from Zhujiang River Delta, southwestward off the Guangdong coast, to the Leizhou Peninsula (Ge et al., 2014; Gao et al., 2015; Li et al., 2022). Subbottom profiles reveal a distinct fine-grained clinoform that forms a high-stand tract system. These deposits have thicknesses of at least 10 m and are homogeneous in structure vertically (Ge et al., 2014).

2.2 Instrument

The sediment acoustic in-situ measurement systems reported since the 1950s can be classified into two main groups in the measurement mode, namely, along-layer and cross-layer systems. The along-layer mode, exemplified by the in-situ sediment acoustic measurement system (ISSAMS) developed by the US Navy (Richardson and Briggs, 1996), involves inserting transmitters and receivers at the same depth below the seafloor to measure the acoustic properties of the sediment at that depth. In contrast, the cross-layer mode, exemplified by the acoustic lance developed by the University of Hawaii (Fu et al., 1996), involves inserting receivers at a certain depth below the seafloor and transmitting wave signals from a source transducer on the seafloor surface or in the overlying seawater, which allows for the measurement of the average acoustic properties of the sediment layers between the sources and receivers. The cross-layer mode is particularly suitable for low-frequency in-situ measurements below 10 kHz because it avoids the need to insert bulky low-frequency source transducers into the seafloor (Yang and Jackson, 2020).

In this experiment, a geoacoustic probe (abbreviated GAProbe hereafter), which employs the cross-layer mode to enable broad band measurements from low to high frequencies, was used. Like the acoustic lance, the GAProbe consists of sound sources, a receiver array, a transmitting/receiving control circuit, and mechanical components (Fig.2a). The sources consist of four customized emission transducers with different central frequencies, covering the entire 5–200-kHz band, each with transmitting voltage responses exceeding 140 dB re 1 μ Pa/V. The receiver array comprises 16 custom-shaped broadband hydrophones that can be embedded in the probe rod for protection, with each hydrophone exhibiting consistent performance and sensitivity better than -205 dB re 1 V/ μ Pa @1 m over the frequency range of 1–200 kHz. The mechanical components of the

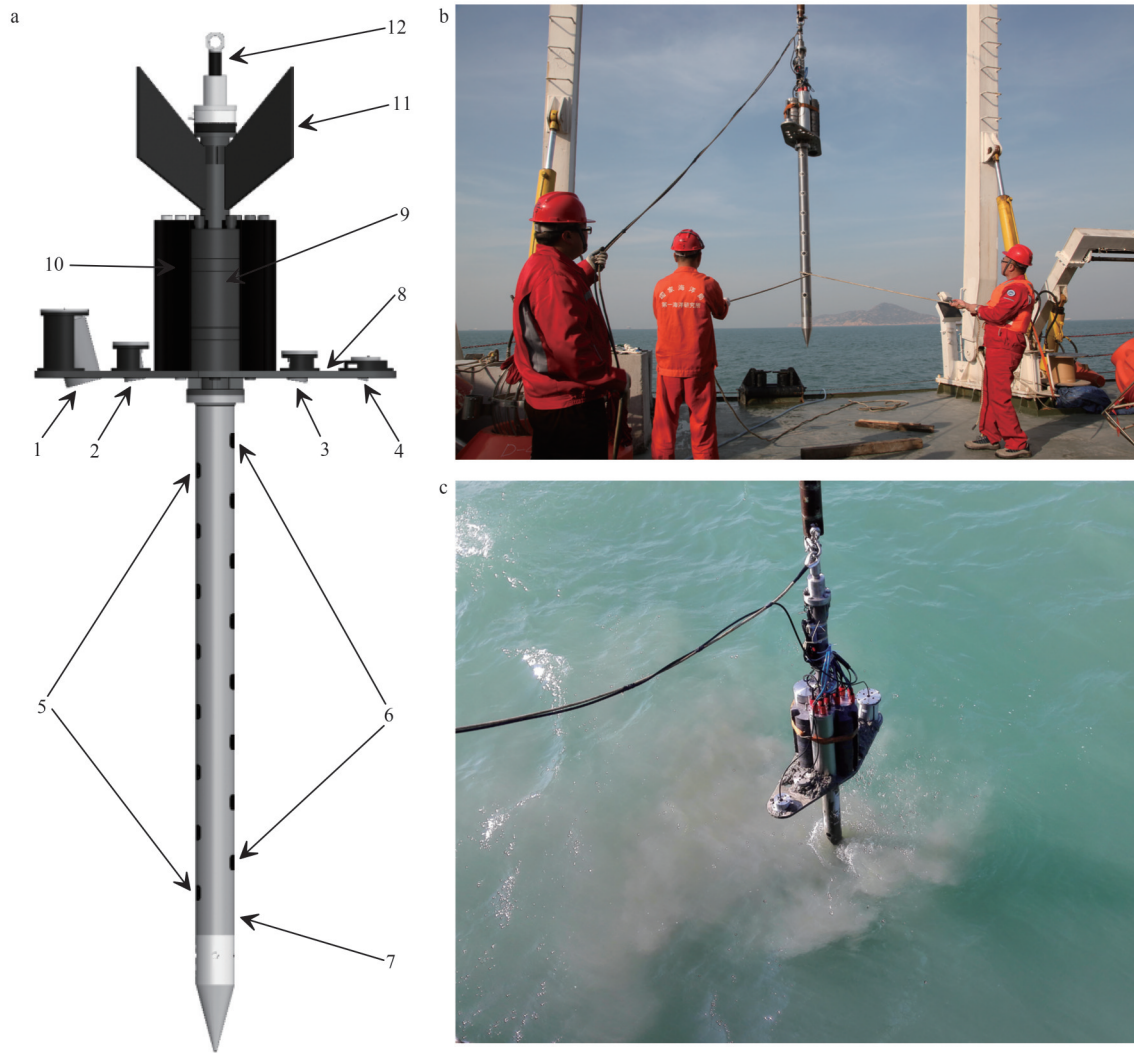


Fig.2 Schematic illustration of the GAProbe structure (a) and photograph of the GAProbe released from the deck (b) and recovered from the seabed, with mud cake on its pallet (c)

Numbers 1–4 represent the source transducers of S1–S4 in Table 1, respectively; 5–6 represent the two groups of hydrophones corresponding to the source of S1–S2 and S3–S4, respectively; 7 represents the probe rod; 8 represents the pallet; 9 represents the pressure housings; 10 represents the weights; 11 represents the stream guide; and 12 represents the lifting element.

system include a probe rod, pallet, pressure housings, weights, stream guide, and lifting element (Fig.2a). The four sound sources, S1–S2 and S3–S4, are positioned on opposite sides of the pallet. Similarly, the hydrophones (R01–R16) are evenly divided into two groups of eight and embedded on one side of the 2-m-long probe rod with a spacing of 0.2 m between each hydrophone. The hydrophones with even number (R02, R04, ..., R16) receive wave signals emitted by sources S1 and S2, whereas the hydrophones with odd number (R01, R03, ..., R15) receive wave signals emitted by sources S3 and S4. The control circuit, which uses field programmable gate array (FPGA) technology, consists of one transmitting channel and eight

receiving channels. During the transmission and reception of sound waves at a specific frequency, the transmitting channel controls the transmission of one of the four sound sources that covers this frequency, whereas the eight receiving channels control the synchronized reception of eight hydrophones corresponding to this source. Once this process is completed, the system proceeds to transmit and receive sound waves at the next frequency. The control circuit is connected to the deck terminal via a coaxial cable for power supply, command interaction, and data upload. The specifications of the main components of the GAProbe are listed in Table 1. The distances between each source and its corresponding receiving

Table 1 Specifications of the main components of the GAProbe

Component	Index	Value
Source	Central frequency (kHz)	8
	Frequency band (kHz)	5–14
	TVR Max (dB re 1 μ Pa/V)	142.6
	Offset from the rod center (mm)	280
	Central frequency (kHz)	35
	Frequency band (kHz)	15–50
	TVR Max (dB re 1 μ Pa/V)	151.1
	Offset from the rod center (mm)	500
	Central frequency (kHz)	80
	Frequency band (kHz)	50–115
	TVR Max (dB re 1 μ Pa/V)	166
	Offset from the rod center (mm)	280
	Central frequency (kHz)	160
	Frequency band (kHz)	115–200
	TVR Max (dB re 1 μ Pa/V)	165
	Offset from the rod center (mm)	500
Hydrophone (R01–R16)	Frequency bandwidth (kHz)	1–200
	Receiving sensitivity (dB re 1 V/ μ Pa @1 m)	≥ 205
	Spacing on the rod (mm)	200
Control circuit	Number of emitting channels	1
	Number of receiving channels	8
Probe rod	Length (mm)	2 000
	Diameter (mm)	127
Whole instrument	Length (mm)	3 700
	Weight (kg)	900
	Maximum operating water depth (m)	1 000

hydrophones were calibrated in a pool using a sound speed meter before the experiment, and these calibrated distances are provided in Table 2. In SBCEX2017, the acoustic coring system (ACS; see Ballard et al., 2020) and sediment acoustic-speed measurement system (SAMS; see Yang and Jackson, 2020) were employed for in situ acoustic property measurements, with the former covering a frequency range of 25–200 kHz and the latter covering a range of 2–10 kHz. The combination of their measurement results was used to reflect the frequency dependence of acoustic properties (Wilson et al., 2020). In comparison, the GAProbe can independently perform in situ measurements across the 5–200-kHz frequency range, not only overcoming the potential difficulties caused by instrument discrepancies in data acquisition and

comparison but also improving measurement efficiency in the field.

2.3 Experiment

The experiment was conducted with the research vessel anchored in place. The GAProbe was initially released into the seawater (Fig.2b) and was positioned 2 m above the seabed. The signal in the water was then acquired eight times, following the predetermined frequencies and transmitting/receiving parameters. In total, 28 frequencies in kHz were tested in sequence, using source S1 and its corresponding receivers (Table 2) for frequencies of 5, 6, 7, 8, 9, 10, and 12 kHz; source S2 and its corresponding receivers (Table 2) for frequencies of 15, 18, 25, 30, 35, 40, and 45 kHz; source S3 and its corresponding receivers (Table 2) for frequencies of

Table 2 Calibrated distances from the sources to the receivers

Source		S1 (8 kHz)	S2 (35 kHz)	S3 (80 kHz)	S4 (160 kHz)	Note
Receiver	Distance $D_{i,j}$ (mm)					
	R01			275.9	468.0	Channel 1 for S3–S4
	R02	502.5	385.5			Channel 1 for S1–S2
	R03			497.7	626.0	Channel 2 for S3–S4
	R04	702.7	617.2			Channel 2 for S1–S2
	R05			741.0	833.6	Channel 3 for S3–S4
	R06	926.5	858.4			Channel 3 for S1–S2
	R07			984.5	1 053.8	Channel 4 for S3–S4
	R08	1 159.6	1 103.7			Channel 4 for S1–S2
	R09			1 229.8	1 285.3	Channel 5 for S3–S4
	R10	1 405.7	1 356.1			Channel 5 for S1–S2
	R11			1 476.9	1 521.5	Channel 6 for S3–S4
	R12	1 647.0	1 604.8			Channel 6 for S1–S2
	R13			1 725.3	1 764.8	Channel 7 for S3–S4
	R14	1 886.2	1 845.2			Channel 7 for S1–S2
	R15			1 968.1	2 003.4	Channel 8 for S3–S4
	R16	2 130.4	2 095.6			Channel 8 for S1–S2

50, 60, 70, 75, 80, 90, and 100 kHz; and source S4 and its corresponding receivers (Table 2) for frequencies of 120, 130, 140, 150, 160, 180, and 200 kHz. Subsequently, the probe was inserted into the sediment, and the transmission-acquisition process in the water was repeated to ensure that corresponding acoustic signals were obtained in both the seawater and sediment at each frequency. The measurement frequency band of 5–200 kHz covered the operational frequency range of most existing in situ acoustic measurement devices and included a threshold frequency below 10 kHz in the Biot theory. This is very advantageous for comparing field measurement data with theoretical models. To calibrate the probe's speed of sound measurement, a sound velocity profiler (SVP) was attached to the probe throughout the experiment. After the measurement was completed, the probe was retrieved at the deck, and the pallet was covered with mud (Fig.2c), indicating that the receiver array was fully inserted into the seafloor and that both the transmitter and receiver contacted the sediment completely.

Next, measurements were conducted at the same location using a ballast in situ acoustic measurement system (BISAMS), a device previously described in Wang et al. (2018) and Li et al. (2019). The

BISAMS was similarly suspended near the seafloor to measure the speed of sound in seawater. It was then inserted into the seabed to measure the speed of sound and attenuation in the sediment. The column sampler, which was mounted on the BISAMS, simultaneously obtained a sediment sample approximately 50 cm in length for laboratory acoustic measurement using the method described by Meng et al. (2012).

2.4 Data processing

A total of 28 frequencies within the range of 5–200 kHz was selected, and the source transducers of the GAProbe in different frequency bands were controlled to sequentially emit wave signals at these frequencies, which were received and acquired by the corresponding receiving array and then uploaded to the deck terminal via a coaxial cable for the calculation of the acoustic properties. The process of transmitting and receiving was repeated eight times for each frequency. The received signals were summed and averaged to minimize the impact of random noise on the data. The waveforms obtained from measurements in seawater and sediment are shown in Fig.3. In seawater, the waveforms of each receiving channel were normalized to the [-1, 1] range, whereas in sediment, they were normalized

based on the seawater waveform of the corresponding channel. As shown in Fig.3a, as the distance from the source increases, the arrival of the waveforms at a frequency of 35 kHz is progressively delayed in both seawater and sediment. Moreover, the waveforms arrive later in the sediment than in the water for each channel, indicating a lower speed of sound in the sediment than in the water (Fig.3a–b). Additionally, the normalized amplitude of the waveforms in sediment is less than that in water (Fig.3a–b). This reduction in amplitude becomes more pronounced with increasing distance from the source, suggesting significant acoustic attenuation in the sediment.

The interreceiver method, proposed by Buckingham and Richardson (2002), was used to calculate the speed of sound and attenuation in an in-situ measurement system with multiple receiving elements. This method eliminates errors caused by narrow-band sources. In our study, we applied this method to the multiple receiving channels of the GAProbe. We extended it by incorporating an intercorrelation plus linear fitting (ICPLF) method, which involves the following steps:

(1) Prior to conducting this experiment, the

source-to-receiver distances $D_{i,j}$ ($i=1, 2, \dots, 4; j=1, 2, \dots, 16$) for each source and hydrophone were calibrated, as detailed in Table 2. Afterward, for each source, the differences in the source-receiver distances Δl_{i1} ($i=2$ to 8) between the seven farthest channels (channels 2 to 8) and the nearest channel (channel 1) can be calculated.

(2) Via the use of the waveforms measured in seawater or sediment from this experiment, the difference in the travel times Δt_{i1} ($i=2$ to 8) between the seven farthest channels and the nearest channel is calculated on the basis of the intercorrelation method, and the relative amplitudes ΔA_{i1} ($i=2$ to 8) of the seven farther channels with respect to the nearest channel are calculated as follows:

$$\Delta A_{i1} = 20 \cdot [\lg(A_i) - \lg(A_1)],$$

where A_1 and A_i are the peak amplitudes of the first and i^{th} ($i=2$ to 8) channels, respectively.

(3) The muddy sediment thickness, as determined by subbottom profiling and coring (Fig.1), exceeds 10 m (Liu et al., 2009; Ge et al., 2014; Shi, 2014). Therefore, it is reasonable to assume that the sediment is homogeneous within the penetration depth of the probe. This allows for the

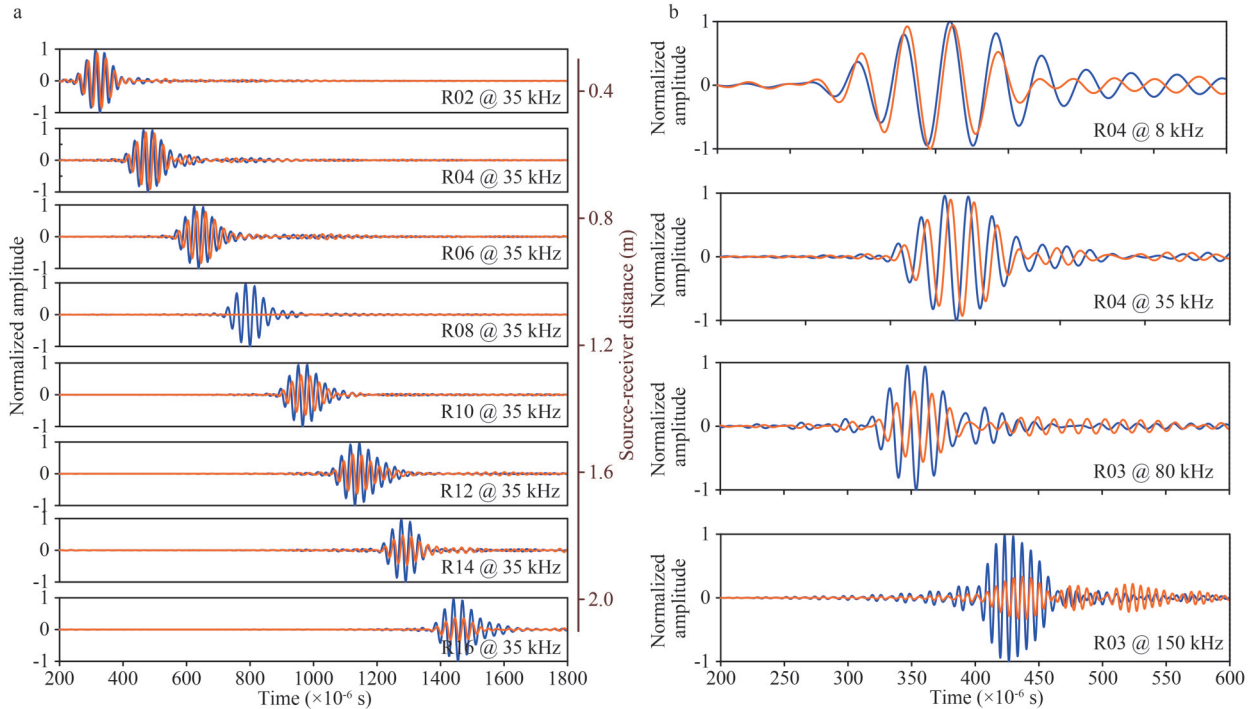


Fig.3 Waveforms acquired with the GAProbe in seawater (in blue) and sediment (in orange)

a. waveforms of each receiving channels (channels 1–8 from top to bottom) at 35 kHz; b. waveforms of channel 2 at different frequencies, which are emitted by sources S1–S4 but not simultaneously. Note that the receiving distance increase from top to bottom in (a) and the different receiving distances from one channel to the four source transducers in (b). The hydrophone R08 (channel 4) appears to have malfunctioned after the probe was inserted into the sediment, so the waveform in sediment was not obtained.

calculation of the mean values of the acoustic properties. To establish the relationships between ΔI_{il} and Δt_{il} and between ΔA_{il} and ΔI_{il} , linear fitting is performed using the least-square method. The resulting slopes represent the mean values of the speed of sound and attenuation in the sediment. Additionally, the uncertainty range of these slopes is calculated to represent the standard deviation of the speed of sound and attenuation.

(4) Finally, the speeds of sound in the sediment are calculated and then normalized by the speed of sound in the water near the bottom to obtain the speed of sound ratio (SSR). This is accomplished using the general calculation method for in situ acoustic measurements (e.g., Wilson et al., 2020; Yang and Jackson, 2020). The speed of sound in seafloor sediments is influenced by environmental parameters such as temperature and seawater pressure. Typically, the speed of sound in sediments is converted to the SSR, which is the ratio of the speed of sound in sediments to that in seawater at the same temperature and pressure. This definition was established by Hamilton (1970, 1980).

3 RESULT

3.1 Speed of sound in seawater

The waveforms acquired in seawater prior to measurements in the sediment can be used to calculate the speed of sound in seawater using the ICPLF method mentioned above. The results of ten measurements of the speed of sound in seawater obtained by the probe, each corresponding to a different signal frequency selected at all twenty-eight frequencies, are shown in Fig.4. These

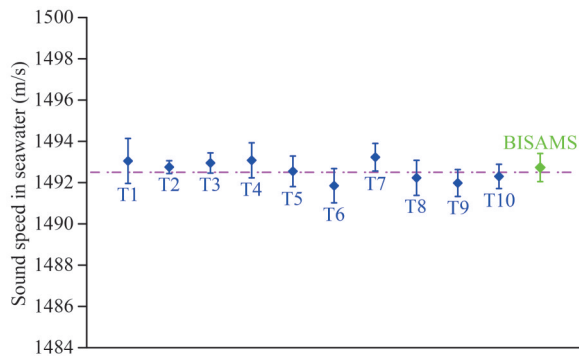


Fig.4 Plot of the speed of sound measured in seawater with the GAProbe (blue circles with error bars), BISAMS (green diamonds with error bars), and SVP (purple dot-dashed lines)

frequencies are 5 and 10 kHz for source S1; 20 and 40 kHz for source S2; 60, 80, and 100 kHz for source S3; and 120, 150, and 200 kHz for source S4; these frequencies are marked in Fig.4 as T1–T10. The figure also includes the speed of sound results obtained using the SVP and BISAMS. The mean values of the speed of sound measured with the GAProbe ranged from 1 491.85 to 1 493.23 m/s, with standard deviations ranging from 0.31 to 1.09 m/s. These values are in excellent agreement with the speed of sound measurements obtained using the SVP (1 492.50 m/s) and BISAMS (1 492.73±0.68 m/s), indicating that the probe measurements are stable and accurate.

3.2 Speed of sound in sediment

The SSR at each frequency measured in the sediment with the GAProbe are shown in Fig.5a. These ratios are obtained by dividing the calculated speed of sound in the sediment by the speed of sound in the seawater near the bottom at the same frequency, as defined by Hamilton (1970). The mean value of the SSR for each frequency ranged from 0.987 to 0.996 and generally increased with frequency. The SSR measured with the BISAMS agree well with those obtained from the GAProbe but have a smaller standard deviation. This could be attributed to the fact that the BISAMS utilizes the along-layer measurement mode, considering the horizontal homogeneity of sediments, which is generally greater than their vertical homogeneity. The SSR of the sediment samples measured in the laboratory at the five frequencies are shown in Fig.5a. Although these measurements exhibit larger standard deviations, their mean values are very close to those obtained from the probe measurements and generally increase with frequency. Errors in measuring the speed of sound arise from inaccuracies in measuring travel time. The errors in measuring the speed of sound across different frequencies are generally consistent, with a SSR uncertainty of approximately ±0.005 and a speed of sound uncertainty of approximately ±7 m/s. Consequently, the measurement error in the speed of sound is relatively minimal.

3.3 Sound attenuation in sediment

The sound attenuation results at each frequency obtained from the GAProbe in the sediment are shown in Fig.5b. The attenuation values depend significantly on the frequency, ranging from 0.29±

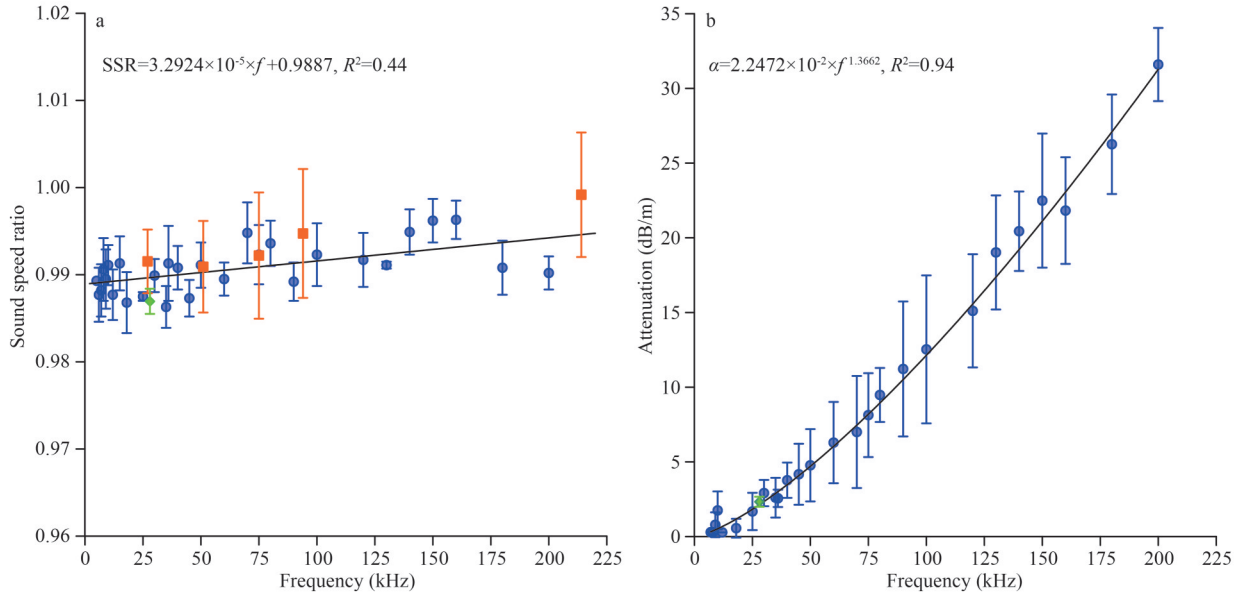


Fig.5 Plot of the speed of sound ratio (SSR) (a) and attenuation (α) (b) measured in sediment at a frequency range (f) of 5–200 kHz with the GAPROBE (blue points with error bars), BISAMS (green diamonds with error bars), and laboratory tests (orange squares with error bars)

The solid lines represent the curves fitting the GAPROBE measurements, and the corresponding equations with coefficients of determination (R^2) are labeled at the top.

0.02 dB/m at 5 kHz to 31.60 ± 2.45 dB/m at 200 kHz. Regression analysis revealed a strong relationship between attenuation (α) and frequency (f , in kHz), as shown in Fig.5b, with a coefficient of determination (R^2) as high as 0.94. The variation in characteristic frequency dependency of the attenuation from f^2 to $f^{1/2}$ in Biot theory was not observed. The attenuation values obtained with the BISAMS align perfectly with the fitted curve derived from the regression analysis. The consistency between the results obtained from the BISAMS and GAPROBE, in terms of both the speed of sound and attenuation, provides some evidence of the accuracy and validity of the probe measurements. However, the attenuation measurements obtained with the GAPROBE exhibit a larger standard deviation than those obtained with the BISAMS do. This discrepancy may be attributed to the different measurement modes employed by the two instruments, as observed in the speed of sound measurements. The errors in measuring attenuation arise from signal amplitude reading errors. On a logarithmic scale, attenuation data points exhibit greater scatter and higher uncertainty at frequencies below 20 kHz. However, the deviation in this study is comparable to or better than that of previous in situ measurements (Williams et al., 2002; Hines et al., 2010; Yang and Tang, 2017).

4 DISCUSSION

4.1 Comparison with previous measurement results

The acoustic properties of seafloor sediment are influenced by the sediment type, in situ state, and sedimentary environment. These properties exhibit temporal and spatial variability, and previous studies have employed various measurement methods, frequencies, in situ environments, and sediment types. Therefore, measurements of the same sediment type must be compared to draw meaningful conclusions.

In a previous study, Hamilton (1980) initially reported that sediments of the same type exhibit similar speeds of sound and physical properties. To quantify these observations, Hamilton calculated and compiled the statistical mean and standard deviation of the measured speed of sound and physical properties for various sediment types on continental terraces (shelf and slope), abyssal plains and hills (Hamilton, 1980). In Hamilton's study, the SSR in clayey silt (YT) was 1.014 ± 0.003 , which is significantly greater than the value presented in this paper. However, recent studies have indicated that Hamilton's statistical results may have overestimated the speed of sound (Jackson and Richardson, 2007; Li et al., 2021). Therefore, to

compare and validate our findings, we collected several, albeit few, in situ measurements that are publicly available in the literature for comparison.

Via the use of the first practical in situ acoustic measurement device, Hamilton used a velocity-attenuation probe (VAP, with frequencies of 14 and 25 kHz) that was deployed by a scuba diver or deep-sea submersible to acquire the SSR and attenuation in clayey silt from the sea area near San Diego, California, USA, with values ranging from 0.970–0.983 and 0.60–5.20 dB/m, respectively (Hamilton et al., 1956; Hamilton, 1963, 1970). Owing to the development of the in-situ sediment acoustic measurement system (ISSAMS, with frequencies of 38 kHz and 58 kHz) by the U.S. Naval Laboratory, some data obtained in the United States, Germany and Italy were published, in which the SSR and attenuation in clayey silt ranged from 0.985–1.003 and 3.60–6.60 dB/m, respectively (Richardson, 1997). In SBCEX2017, a low-frequency (2–10 kHz) in situ acoustic measurement system called the sediment acoustic-speed measurement system (SAMS) was used to determine that the speed of sound at the NEMP ranges from 0.980–1.000 (Wilson et al., 2020; Yang and Jackson, 2020). Newly published data acquired with the BISAMS in the East China Sea revealed a SSR and attenuation in the range of 0.969–1.005 and 0.26–1.17 dB/m, respectively, in area C, where clayey silt sediments

are dominant (Wang et al., 2023). These data are projected in Fig.6a & b according to their frequency ranges. The larger range of variability is attributed mainly to these statistical results being from multiple stations, and the sediment varies considerably in composition from station to station, even though they are of the same clayey silt sediment type.

The results of this study are consistent with those of previous studies, except for the speed of sound values studied by Hamilton (1980). Hamilton used primarily sampling measurement methods, which have high measurement frequencies and may be affected by environmental changes, leading to inaccurate sound attenuation data. In contrast, the data from other studies, shown in Fig.6, were obtained via the use of in-situ measurement technology. This technology reduces disturbances to the sediment structure and state, resulting in more accurate acoustic property data that align with the actual seafloor sediment conditions. Therefore, the in-situ measurement results from different studies are more consistent with each other than the laboratory measurement results are.

4.2 Frequency dependence and modeling

According to the results of this experiment, clayey silt is acoustically dispersed, with a weak positive linear correlation between the SSR and

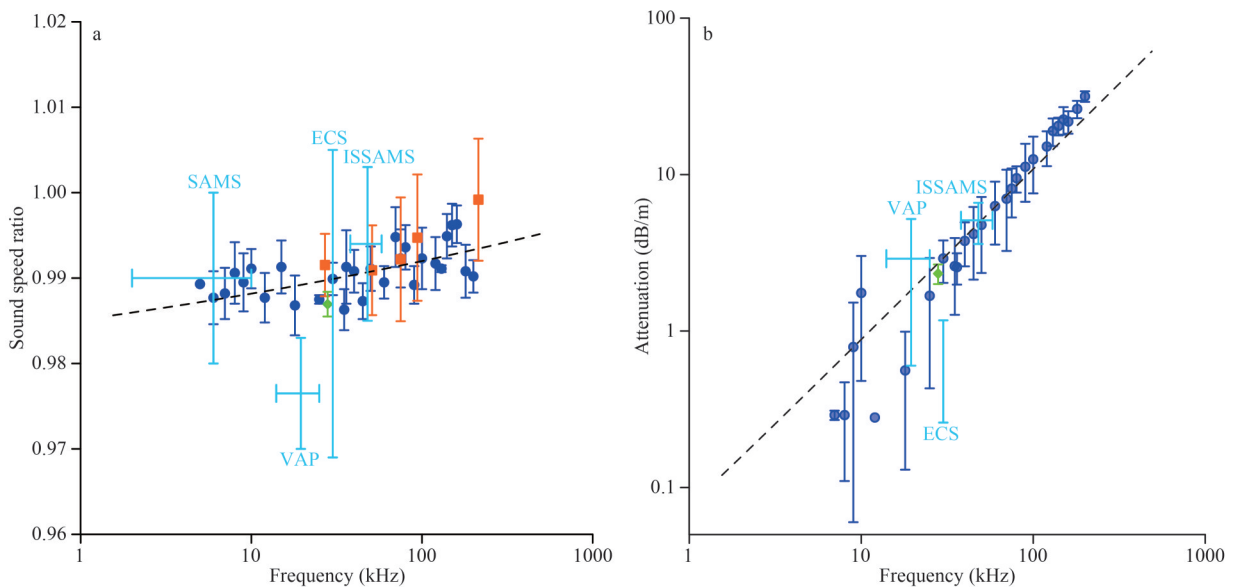


Fig.6 Comparison of the measured acoustic properties (with the same symbols as in Fig.5) with the previously published properties (sky blue error bars to show their range) and the modeling results (dashed lines)

a. the speed of sound ratio; b. the attenuation. The VAP data are from Hamilton et al. (1956) and Hamilton (1963, 1970), the ISSAMS data are from Richardson (1997), the SAMS data are from Yang and Jackson (2020), and the ECS data are from Wang et al. (2023).

frequency and an exponential positive correlation between attenuation and frequency. A weak correlation between the SSR and frequency for clayey silt was also observed in laboratory measurements of samples collected in the South Yellow Sea, South China Sea, and West Pacific, which also revealed a gradual decrease in the dispersion effect as the sediment became finer (Kan et al., 2018; Wang et al., 2022).

Initially, a linear relationship between attenuation (α) and frequency (f) was accepted by many authors (Hamilton, 1980), and researchers now prefer using nonlinear exponential functions in the form of $\alpha(f) = \alpha \cdot f^b$ after extensive experimentation but with large differences in the determination of the index b (Zhou et al., 2009). Unlike the relatively larger b in sandy sediments, the value of 1.12 was obtained by Bowles (1997) by fitting tens of compiled attenuation data points at frequencies from 10 Hz to 500 kHz in fine-grained marine sediments. The inverted attenuation at the low-velocity bottom of the south Yellow Sea studied using long-range inversion techniques by Zhou et al. (2024) approximately follows a linear frequency dependence with $b=1.0032$ for a frequency band of 13–5 000 Hz. The attenuation measured in this experiment also follows an exponential relationship with frequency, with a b value of 1.3662, which is greater than that given by Bowles (1997) and Zhou et al. (2024) but much less than that for sandy sediments. The attenuation data used by Bowles (1997) included many sediment types, not only fine-grained sediment such as clay and silty clay but also relatively coarser silt, clayey silt, and sandy silt-clay, which were generally classified as fine-grained sediment. According to Zhou et al. (2024), the sea bottom is covered mainly by silty clay. Considering that the sediment at this experimental site is clayey silt, the difference in the index b may be attributed to the variation in sediment type; namely, the coarser the sediment grains, the greater the b value.

Acoustic dispersion in sandy sediments is well understood, but there is still uncertainty regarding the dispersion of the acoustic properties of fine-grained sediments (Wilson et al., 2020). Two theories, Biot theory and viscous grain-shearing (VGS) theory, have been used to interpret and model the dispersion characteristics of acoustic properties. Biot theory and its derivatives, such as the Biot-Stoll model (Biot, 1956a, 1956b; Stoll, 1977), effective density fluid model (EDFM; see Williams, 2001), and extended Biot model (EB; see Chotiros,

2017), consider the sediment as a two-phase system consisting of grains (the elastic frame) and water (the fluid). These theories assume that the grains and water may move with different displacements when a wave is excited. However, whether the assumption of an elastic frame is valid for unconsolidated sediment, where the grains are in contact but mobile relative to one another, is unclear (Buckingham, 2014). On the other hand, VGS theory, derived from the Navier-Stokes equation, accounts for the stresses present at the intergranular contacts and attributes dissipation and dispersion to the strain hardening mechanism. VGS theory is physically based and can accurately model the frequency dependence of the SSR and attenuation in both sandy and muddy sediments (Ballard and Lee, 2016; Buckingham, 2020). Model fitting revealed that the Biot model was more suitable for high-velocity sandy seabeds, whereas the VGS better matched attenuation at the low-velocity muddy bottom. Additionally, the measured attenuation scales with frequency, as shown in Fig.5b, without the characteristic threshold frequency observed in Biot theory from f^2 to $f^{1/2}$. Therefore, VGS theory is used in this study for modeling and comparison with the measured results.

The input parameters used for VGS modeling are listed in Table 3. The viscoelastic time constant and strain hardness index, as well as the physical parameters of grains and pore water, are assigned generic values for muddy sediments based on Buckingham's suggestions (Buckingham, 2020). The porosity and mean grain size are set to average values from the mud area derived from the Zhujiang River (Shi, 2014). The curves modeled for the SSR and attenuation are shown in Fig.6a & b, respectively. Overall, there is good agreement between the measurements and predictions from VGS theory, with the predicted curves falling within the error bars of both the SSR and attenuation. The low acoustic dispersion observed in fine-grained sediment aligns with the physical mechanism of VGS theory. As the porosity of the sediment increases, the interaction between grains weakens, making the sediment behave more like a suspension. This results in a frequency-independent speed of sound, as described by Wood's equation (Buckingham, 2005). Additionally, the effective viscosity of the thin layer of seawater between grains (function $g(w)$ in Eq.(35) of Buckingham (2007)) in fine-grained sediments approaches unity, leading to attenuation scaling with the first power of frequency (smaller index b in the $\alpha(f)=\alpha \cdot f^b$

Table 3 Parameters input into VGS theory for geoacoustic dispersion modeling

Physical parameter	Symbol	Unit	Value	Note
Bulk modulus of grains	K_g	Pa	7.3×10^{10}	$K_g = \frac{E}{3(1-2\sigma)}$
Density of grains	ρ_g	kg/m ³	2 750	From Buckingham (2020)
Poisson's ratio of grains	σ	—	0.25	From Buckingham (2020)
Young's modulus of grains	E	Pa	1.1×10^{11}	From Buckingham (2020)
Bulk modulus of pore water	K_f	Pa	2.395×10^9	From Buckingham (2020)
Density of pore water	ρ_f	kg/m ³	1 023	From Buckingham (2020)
Speed of sound of pore water	c_w	m/s	1 512.4	From Buckingham (2020)
				Calculated using equation
Porosity	N	—	0.72	$N = 1 - P_s \left\{ \frac{u_g + 2\Delta}{u_g + 4\Delta} \right\}^3$ where the grain diameter $u_g = 9 \mu\text{m}$ in this study, the packing factor $P_s = 0.63$, and the rms roughness $\Delta = 2 \mu\text{m}$, according to Buckingham (2005)
Mean grain size	u	ϕ	6.77	From Shi (2014)
Depth in sediment	d	m	1.0	Half of the penetration depth of the GProbe
Viscoelastic time constant	τ	ms	∞	From Buckingham (2020)
Strain hardness index	n	—	0.088 54	From Buckingham (2020)

relationship) compared with that in sandy sediment. The frequency dependence of VGS attenuation at high frequency is approximately f^1 , which matches the measured attenuation. In contrast, the frequency dependence of Biot theory-based attenuation at high frequency is closer to $f^{1/2}$.

The model accurately captures the SSR curve within the measurement frequency range. However, the predicted attenuation curve deviates to some extent, particularly at frequencies above 120 kHz and below 20 kHz. This is the first report of broadband geoacoustic measurements in fine-grained sediment using a single instrument, which presents a significant challenge for measuring low-frequency in situ attenuation while simultaneously balancing high-frequency measurements. The difference in amplitude of the low-frequency sound signals between sediment and seawater is relatively small, as shown in Fig.3a. However, background noise can affect the amplitude reading, leading to uncertainties in the calculation of low-frequency sound attenuation. This is a limitation of the current measurement technology. Future work should focus on improving the attenuation measurement technique and expanding the frequency range toward low frequency. Additionally, sediment heterogeneity might be another factor whose influence on attenuation far exceeds its impact on

the speed of sound. Unfortunately, no sediment samples were collected in this experiment; thus, this point cannot be confirmed. In the future, more data collection and analysis are needed to establish a statistically significant relationship for the frequency dependence in fine-grained sediments.

5 CONCLUSION

This study focuses on the in situ measurement of the acoustic properties of fine-grained sediments using a newly developed instrument, namely, the geoacoustic probe. The speed of sound and attenuation at a frequency of 5–200 kHz in clayey silt in the Zhujiang River estuary were obtained in this experiment. To ensure the accuracy of the geoacoustic probe, the speed of sound in seawater was calibrated, and the obtained measurements were compared with data from other in situ and laboratory methods. Through the analysis of measurement data and comparison with theoretical models, the following conclusions are obtained:

(1) The results confirmed the reliability and precision of the geoacoustic probe and demonstrated the advantage of the probe in achieving in-situ, wide-band acoustic property measurements.

(2) The SSR was consistently less than 1, indicating slower sound propagation in the clayey silt sediment. The degree of sound attenuation was

lower than that in sandy sediment at the same frequency. Both the measured SSR and attenuation fell within the range of in situ measurements in fine-grained sediment reported by previous researchers.

(3) A weak linearly increasing SSR and an increasing attenuation of the near $f^{1.36}$ dependence with frequency were observed and approached the predictions of the viscous grain-shearing theory.

Overall, this study demonstrates a successful approach to wide-band in situ geoacoustic measurements, and the results provide valuable insights into the acoustic properties of fine-grained sediments, specifically clayey silt. The findings contribute to our understanding of sediment characteristics and have implications for various scientific and engineering applications.

6 DATA AVAILABILITY STATEMENT

All the data generated and/or analyzed during this study are available from the corresponding author upon request.

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