Development and preliminary application of a minimum axle-distance triaxial measurement system for the acoustic characteristics of marine sediments

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Abstract. The seabed sediments have different original stress states. It is of great significance to study the acoustic characteristics of sediments in different stress states. By adding an acoustic device into the geotechnical Global Digital Systems (GDS) stress path triaxial system, a minimum axle-distance triaxial measurement system for the acoustic properties of seabed sediments is developed. The GDS triaxial system is used to simulate the in-situ stress state of sediments, and the acoustic measurement system is used to measure the sound attenuation and sound velocity of them. The reliability of the developed measurement system is verified by the pure water calibration test. Then, the sound attenuation and sound velocity of triaxial specimens of the sandy sediments in Hangzhou Bay, China, are tested with different effective stresses and excitation frequencies. Test results are consistent with the existing acoustic theory of marine sediments, which verifies the effectiveness of the developed measurement system. It indicates that the developed measurement system can be applied to study the acoustic properties of seabed sediments in different original seabed stress states.

1. Introduction

Researches on the degree of energy loss and propagation time of sound waves propagating in the seabed sediments can provide a lot of information concerning physical and mechanical properties of sediments [1]. Among them, sound velocity and sound attenuation, as the basic parameters that carry information about the acoustic property, are necessary to study the sound propagation theory of seabed sediments and the acoustic modeling [2, 3]. At present, there are mainly three methods in studying the sound velocity and sound attenuation of the seabed sediments: (1) non-contact measurement method [4]; use seabed remote sensing devices for non-contact measurement. It causes hardly any disturbance to the sediments and can be used to detect sediments in a large area within a relatively short period of time.
Also, the method can predict the type and layering characteristics of the seabed sediments. However, the measurement result is low in accuracy, and easy to be disturbed by different environments. (2) In-situ measurement method [5]: researchers can obtain the most reliable acoustic parameters and can avoid errors caused by interference during the sampling and transportation process by the in-situ measurement equipments. However, applying such method needs to meet extremely high requirements during the operation. Moreover, the measurement results reflect the combined effects produced by various environmental factors in the natural seabed. Hence, the technical operation and data analysis are difficult and time-consuming. (3) Laboratory measurement method [6]: due to the financial and technical limits, this method is usually used in studying the acoustic properties of the seabed sediments. Although the measurement of samples will inevitably disturb the original state of sediments, the method has a few of advantages, such as the simple operation, the controllable condition, and the high measurement accuracy. It is widely acknowledged as an effective method for acoustic measurement of the seabed sediments.

Laboratory measurement methods include the following steps: sampling, storage, and transportation, measurement of physical and mechanical acoustic properties of samples, and processing of the data. Among all of the steps, the measurement of physical mechanics and acoustic properties is the key link. Therefore, researchers have developed different equipments to measure the physical, mechanical, and acoustic properties of the sediments. Wu et al. [7] designed a cone-shaped transducer with a diameter of 20 mm to measure the sound attenuation of the sediments. The cone-shaped transducer can effectively reduce the disturbance by inserting the equipment into the sediments. However, the diameter of the used PVC equipment is 75 mm (too large); and they ignored the actual stress conditions of the sediments. Wang et al. [8] used an autoclave to pressurize the sediments, which can measure the sound velocity and sound attenuation of the sediments under the pressure within 1000 m of water depth. The sound attenuation was obtained by measuring the sound intensity. Long et al. [9] developed a novel acoustic wave instrument and combined it with a customized triaxial shear equipment. This equipment can simulate the seabed sediments at a depth of 200 m under different stress states, and obtain their changes in sound velocity. However, it was unable to measure the sound attenuation. Zou et al. [10] developed an acoustic measurement system with the controllable temperature and pressure, which has the capacity to measure sound velocity of the seabed sediments at different temperatures in a water depth of 2000 m.

At present, the laboratory measurements are mainly focused on the shallow surface sediments of the seafloor. Thus, the instruments and equipments can only be applied to simulate the stress condition of shallow sediments and measure them with the surrounding pressure is equal to the hydrostatic pressure [11]. However, for the deeper sediments below the surface of seabed, the consolidation and deformation of sediments could occur under the self-weight stress, and the pore water pressure in the soil could gradually dissipate and transform into the effective stress [12]. The measurement apparatus for sound velocity and attenuation of the seabed sediments in the state with different effective stresses is still lacking.

Based on the penetration theory of sound attenuation, a minimum axle-distance triaxial measurement system is developed. Combined with the GDS stress path triaxial instrument, the system can measure sound velocity and sound attenuation of the seabed sediments under different in-situ stress conditions. Firstly, a pure water calibration test is used to verify the feasibility of the equipment; then, based on the measurement system, acoustic tests of the triaxial sandy specimens collected from Hangzhou Bay, China, are conducted to analyze and verify the effectiveness to measure the acoustic properties of seabed sediments.

2. Measuring principle
Macroscopic parameters, such as the sound velocity, sound attenuation, and elastic coefficient of the matter can be obtained from the interaction between sound wave and matter. Macroscopic parameters can reveal some microscopic nature of the matter. Therefore, by using the high-frequency sound waves generated by the P-wave transducer that penetrate the seabed sediments, the characteristic parameters carrying the internal information of the seabed sediments, such as the speed of sound waves, sound attenuation, and other parameters can be extracted [13].
The sound attenuation of sediments can be obtained by the following formula [14]:

$$\alpha = \frac{20 \log(A_1/A_2)}{(L_2 - L_1)}$$  \hspace{1cm} (1)

In formula (1): $\alpha$ is the sound attenuation of the sediment, dB/m; $L_1$ and $L_2$ are the distances between different measurement points of the sediment and the sound source, m; $A_1$ is the sound pressure amplitude measured at a fixed distance $L_1$ of the sediments, $\mu$Pa; $A_2$ is the sound pressure amplitude measured on a fixed distance $L_2$ of the sediments, $\mu$Pa.

The sound velocity of sound wave in the sediments can be obtained by the following formula:

$$c = \frac{l}{t}$$  \hspace{1cm} (2)

In formula (2): $c$ is the speed of sound in the sediment, m/s; $l$ is the propagation distance of the sound wave in sediments, m; $t$ is the penetration time of the sound wave in the propagation distance, s.

In this work, the distance between the excitation and the receiving end is designed according to the requirement $l > \nu/f$, which is coaxial with the sediment specimen [15]. The primary waves method [16] is used to extract the propagation time $t$ and amplitude $A$ of acoustic signals from the acoustic diagram. Sound attenuation and sound velocity of the sediments can be calculated from the equations (1) and (2).

3. Development of the measurement system

3.1. System composition

Based on the geotechnical GDS stress path triaxial device, a minimum axle-distance triaxial measurement system for the acoustic properties of the seabed sediments is developed. The GDS triaxial system is an advanced indoor laboratory soil test [17], which can individually control the confining pressure, axial pressure, and pore pressure of the experimental specimen, by using three independent controllers. The maximum working pressure of controller is 2 MPa, the volumetric drainage accuracy is 1 mm$^3$, and the pressure variation accuracy is 1 kPa. The controller can accurately control to simulate the complex stress states of soil specimens, and the parameters of soil strength, strain deformation, pore pressure dissipation coefficients, static lateral pressure coefficients, and permeability coefficients can be determined. As the compatibility of GDS system is strong, an independent temperature control equipment and a volumetric measurement device can be added into it [18]. An advantage to use the GDS stress path triaxial instrument is to precisely simulate the in-situ stress state of seabed sediments in control.

Figure 1(a) is a schematic diagram of minimum axle-distance triaxial measurement system for the acoustic characteristics of seabed sediments. It is characterized by using a function signal generator to generate electrical signals, which are amplified by a linear amplifier and transmitted to the excitation end of the P-wave transducer to excite P-waves. At this time, two micro hydrophones receives the P-wave in a triaxial specimen, then the P-wave is amplified by the charge amplifier and transmitted to the oscilloscope for display and recording. Finally, the received P-wave is analyzed and processed by a

**Figure 1.** The triaxial acoustic measurement system (a) schematic diagram, (b) profile display.
Figure 1(b) is the profile display of the minimum axle-distance triaxial measurement system for the acoustic properties of seabed sediments. The AFG1062 Tektronix Function Signal Generator is selected, its output signal peaked at ±10 V. Piezo EPA-104-230 Linear Amplifier is selected to amplify the original excitation signal by 0–20 times. The protection input and output voltage peaks of the equipment are ±10 V and ±200 V, respectively. The MSO5 Tektronix Hybrid Oscilloscope is used, which has multiple mathematical function modules. In the initial calibration module, the system delay can be eliminated by setting a mode of the automatic elimination of system delay. In addition, the frequency domain of the received signal can be analyzed, too. The Vking Charge Amplifier is selected with a gain of 20 dB, and an adjustable DC stabilized power supply is used to provide 12V DC stabilized voltage for the charge amplifier.

3.2. P-wave transducer

The piezoelectric ceramic material selected in this work is produced by Piezo Systems [19], which specific parameters are shown in Table 1.

| Diameter (mm) | Thickness (mm) | Temperature Range (℃) | Resonant Frequency (kHz) | Production Batch Number |
|--------------|----------------|------------------------|--------------------------|------------------------|
| 12.7         | 0.41           | -60–140                | 1.17                     | T216-A4-NO273X          |

The specific production process of the P-wave transducer is shown as follows:

1) Use the cables with high signal to noise ratio and high voltage resistance. The wiring method is that the red wire connects the positive electrode, the black connects the negative electrode, and the other colors connect the ground wire. The red and black wires in the cable are respectively welded to the front and back of piezoelectric ceramics, and the green wire is welded to the inner surface of the metal shell, as shown in Figure 2.

2) Eseller-ayat et al. [20] and Deniz [21] studied the effects of different waterproof materials on the performance of P-wave transducers. They found that the epoxy resin glue is a more suitable waterproof material for bonding other materials under the low stress conditions. The selected glue is EPO-TEK-301-2 two-component epoxy resin, which is abbreviated as glue A and glue B. The mixing ratio (A: B) is 4:1. Mix the glue A and glue B for 3–5 minutes and wait for about one hour.

3) Draw a fixing line between the piezoelectric ceramics and the metal shell on the surface of the PTFE material. Then, fix the piezoelectric ceramic sheet and the metal shell according to the fixing line. Meanwhile, the bottom surfaces of the two parts should be kept on the same horizontal plane, and the central axis should be coaxial, as shown in Figure 3. Use a syringe to inject a few of semi-solid glue into
the cavity of the metal shell, let the glue solidify until it overcomes its own weight, and then turn it over by 180°. Drip a small amount of the semi-solid glue gently and smooth it evenly on the top surface of the piezoelectric ceramics. Thus, the piezoelectric ceramics, soldering points, and bare cable parts are all wrapped in epoxy resin with a thickness of about 1–2 mm. After the glue is air-dried, the process of making P-wave transducer is completed.

4) Lead the cable of the P-wave transducer out of the side of the sample cap, and place the P-wave transducer in the middle of the upper and lower sample caps, so that the P-wave transducer and the sample cap can be in contact with the soil specimen. The surface of P-wave transducer is kept on the same horizontal plane with the sample cap, and the central axis of them are coaxial; an O-ring seal is provided for sealing the P-wave transducer into the sample cap, as shown in Figure 4.

![Figure 4. The P-wave transducers in sample caps.](Image)

The following two points need to be paid attention in process of producing the P-wave transducer:

1) Noticing the correct wiring method of the piezoelectric ceramics

Since the electromagnetic coupling disturbs the excitation signal of the piezoelectric ceramics, such phenomenon is defined as crosstalk. Lee et al [22] believes that crosstalk is an electromagnetic field formed by the interaction between the electric field generated by the alternating current in the air and the magnetic field generated by equipment components. The electromagnetic field is converted into an electric signal that propagates fast and interferes with the P-wave at the receiving end. According to the basic principle of the Faraday Cage [23], the piezoelectric ceramics is placed in a metal shell, and the metal shell is connected to the twisted wire in the cable. Moreover, wiring of each circuit is correct, forming a closed-loop shielded channel in the signal circuit, so that the electrical signal in the shielded channel could not be affected by the external electric field.

2) Considering waterproof and pressure resistance of the piezoelectric ceramics

When the piezoelectric ceramics is placed in water, the water resistance must be considered because it has an exposed electrode on the surface; when the P-wave transducer is embedded in soil, the piezoelectric ceramics is excited by electrical signals and need to exert piezoelectricity. The ceramics sheet should expand or contract flexibly to prevent any external impact from being damaged. Therefore, the selected material must meet the requirements of waterproof and pressure resistance. At the same time, it is banned from affecting the expansion and contraction performance of the piezoelectric ceramics.

3.3. Miniature hydrophone probe

The miniature hydrophone probes are produced from Hongzhi Transducer Technology Co., Ltd. The frequency response range of them is 30 kHz–300 kHz, and the sensitivity -210 dB--195 dB (reference value 1 V/μPa). The diameter of the probe is 3 mm, and the length of the probe section 50 mm. Since the diameter of probe is much smaller than the wavelength, and the contact area between the probe and the sediment triaxial specimen is small, there is little disturbance to the triaxial specimen and the sound field during a test. Specific size parameters of the miniaturized hydrophone probe are shown in Figure 5.

The head of the miniature hydrophone probe must be inserted into the soil specimen wrapped in a latex membrane. The phenomenon of water leakage should be prevented at the position. After comparative experiments of different materials, it is found that the flexibility of silicone material has good adhesion between the latex membrane and stainless steel. Meanwhile, it is an effective
waterproof material to avoid influences on the specimen deformation. Using a 3D printer, the silicon material is produced into a silicon ring. The silicon ring is divided into two parts: the extension ring and the probe ring. The extension ring is attached to the inner wall of the sample latex membrane, while the probe ring is used to wrap the miniature hydrophone probe. The schematic diagram of the silicon ring model is shown in Figure 6.

![Figure 6. Schematic diagram of the silicon ring model.](image)

When the hydrophone probe is inserted into the soil specimen, the piezoelectric ceramics inside it can receive the mechanical vibration transmitted by the soil particles, and it generates an electric potential difference between the two poles of the piezoelectric ceramics, thereby converting the mechanical vibration into an electrical signal, and passing the electrical signal through the charge amplifier to the oscilloscope for display.

4. Calibration of the acoustic measurement system

4.1. Pure water calibration test

The pure water (25 °C) in a plexiglass tube is used as the acoustic transmission medium to examine the response of the miniature hydrophone probe and the P-wave transducer. The sine electrical signal [24] is used to excite the P-wave transducer, and its frequency varies from 30 kHz to 300 kHz, which is covered by the main frequency range of the micro hydrophone probe. The detailed steps are as follows:

As shown in Figure 7, the excitation end of the P-wave transducer is placed at the bottom of the plexiglass tube, and equal and unequal distance acoustic calibration tests are conducted in the pure water. The equal distance represents that the two miniature hydrophone probes are placed vertically on the same horizontal plane, and are equidistant from the axis of the P-wave transducer, as shown in Figure 7(a). The unequal distance means that the micro hydrophone probes are placed according to the coaxial gap method [25]. Mark the lower hydrophone probe as No. 1 and the upper as No. 2. After the probes

![Figure 7. Pure water calibration Test (a) equidistant test, (b) unequal distance test.](image)
penetrate into the center of the plexiglass tube, seal the measuring hole with a rubber stopper, as shown in Figure 7(b). Use a vernier caliper to read the vertical distance between the two probes and the two P-wave transducers. It is 271.4 mm at equal distances, and 34.2 mm and 80.4 mm at unequal distances.

4.2. Calibration results
As shown in Figure 8, in the equidistant test (Figure 8(a)), the amplitudes of the first half of the primary waves arrive at two miniature hydrophone probes are almost the same, while the waveforms of the second half are slightly different. In the unequal distance test (Figure 8(b)), the waveforms received by the two hydrophone probes are similar, and the amplitude of the first wave received by the two probes (No. 1 and No. 2) is 71.36 mV and 70.65 mV, respectively. The measurement accuracy is 0.01 mV. The primary wave method is used to record the time and amplitude of the signals during the calibration tests. Based on the formulas (1) and (2), the average sound velocity and sound attenuation of P-wave in pure water are calculated for 1498.6 m/s and 0.0018 dB/m, respectively. At 25 °C, the sound velocity of P-wave in pure water is 1498.9 m/s [26], and the sound attenuation 0 dB/m. The sound velocity of the pure water in the acoustic tests only differs from the statistical value by 0.3 m/s, and the sound attenuation is slightly different. There may be two reasons for the differences: ① The vibration stiffness of the two hydrophone probes differs due to the manufacturing process, such as the thickness of glue or the insertion depth of the piezoelectric ceramics. ② In the actual test, there are a small amount of bubbles in pure water and the bubbles have a significant attenuation effect on acoustic wave propagation [27].

Figure 8. Results of the pure water acoustic tests (a) equidistant test, (b) unequal distance test.

The manufacturing process may cause the main frequency range of the piezoelectric ceramics to fluctuate, such as the welding procedure of the piezoelectric ceramics and variations in coating thickness. Therefore, it is necessary to examine the P-wave transducer before a test and determine the main frequency range. Under the excitation of electrical signals of different frequencies, there is no obvious electromagnetic coupling phenomenon in the P-wave transducer during the test, and the P-wave transducer and the two hydrophone probes have a good performance in response. Before the unequal distance test, the acoustic wave signals received by the two miniature hydrophones are analyzed in the frequency domain [28], and the main frequencies of the P-wave transducer are 40–55 kHz and 220–270 kHz.

In summary, the results of the sound velocity and sound attenuation of the pure water acoustic test prove that the difference between the two hydrophone probes is small, and the accuracy is high. Moreover, there is no obvious electromagnetic coupling phenomenon between the P-wave transducer and the entire system. Therefore, the acoustic measurement system is feasible, and the acoustic test of the sediments can be performed under the triaxial stress condition.

5. Initial application

5.1. Test materials
The sediments samples used in the test are taken from the seabed sandy sediments of Hangzhou Bay and
passed through a 2 mm sieve after air-drying. The measured specific gravity \( G_s \) is 2.68, the minimum void ratio \( e_{\text{min}} \) 0.739, and the maximum void ratio \( e_{\text{max}} \) 1.239. Figure 9 shows the particle size distribution curve of the submarine sandy sediment in Hangzhou Bay. It can be seen that the main particle size of the sediments ranges from 0.075 mm to 0.25 mm, and the fine particle content is about 10%.

![Particle size distribution curve](image_url)

**Figure 9. The particle grading curve of sediments samples**

5.2. Specimen preparation and installation

The triaxial specimen of sandy sediments is prepared according to the falling sand method \([29]\) in the triaxial chamber with the relative density 30%, diameter 50 mm, and height 100 mm. It should be ensured that the P-wave transducer, the sediment triaxial specimen, and the heads of the two hydrophone probes are installed coaxially. The specific steps are as follows:

1) According to the requirement of distance \( l > \frac{\nu}{f} \), the P-wave velocity of submarine sediments is generally reported 1300~1900 m/s \([30]\). Applying the maximum wave velocity \( \nu = 1900 \text{ m/s} \) and the lowest frequency \( f = 45 \text{ kHz} \) into the wavelength formula, the minimum distance is calculated to be 42.2 mm. As shown in Figure 10, the positions of two customized opening holes on the mold cylinder should meet the minimum distance requirement, and the diameter of hole is 5 mm. The opening hole is used to fix the micro hydrophone probes and the distance is the same in each test.

2) According to the position of two holes on the mold cylinder, open the corresponding holes on the latex membrane, and then pass the silicon ring out of the opening holes. The extension ring of the silicon ring and the inner side of the latex membrane are glued together. After the glue is solidified, the latex membrane is sleeved into the mold cylinder, and the probe ring of silicon ring is penetrated from the corresponding holes of the mold cylinder. Lastly, the mold cylinder is fixed on the specimen pedestal of the GDS triaxial instrument.

3) Before a specimen preparation, weigh 252 g of the dried sandy sediments, use a 10 mm funnel to divide the sand samples into five layers, and pour them into the molding cylinder covered with latex membrane. The funnel should be slightly higher than the upper surface of the specimen. At the same time, use a rubber hammer to lightly tap the mold cylinder to obtain the same height of each layer of the sandy sediments, i.e., to complete the preparation of a uniform cylindrical triaxial specimen.

4) Put the O-shaped sealing ring on the hydrophone probe, and gently insert the probe from the probe ring fixed in the mold cylinder into the center of the specimen. Then use a level with a scale to ensure that the insertion depth is the same in each time. Lastly, hoop the O-ring on the probe; then place the sample cap horizontally on the triaxial specimen, turn over the latex membrane and tie tightly with some rubber bands.

5) The specimen is vacuumed, and the negative pressure is no less than -10 kPa. When the specimen with the two hydrophone probes can stand upright, remove the mold cylinder. Thus, the process of specimen installation is completed, as shown in Figure 11.
Figure 10. The cylinder forming mold. Figure 11. The prepared specimen in triaxial chamber.

5.3. Test plan
The sound velocity and attenuation at different frequencies under different effective stresses with the same effective confining pressure are measured for triaxial specimens at a constant temperature (25°C).

1) Applying effective stress to triaxial specimens. To simulate the in-situ effective stress the sediments in the seabed, the Terzaghi principle of effective stress [31] is generally applied, i.e., effective stress $\sigma' = \sigma_3 - u$. The confining pressure controller is used to exert surrounding pressure on the specimen $\sigma_3$ (hereafter referred to as confining pressure $\sigma_3$), and the backpressure controller is used to exert pore water pressure $u$ (hereafter referred to as pore pressure $u$), namely, the effective stress is controlled by the effective confining pressure. The specific test scheme is shown in Table 2.

| Sample Number | Effective Confining Pressure $\sigma'$ (kPa) | Pore Pressure $u$ (kPa) | Confining Pressure $\sigma_3$ (kPa) |
|---------------|------------------------------------------|------------------------|----------------------------------|
| 1#            | 100                                      | 500                    | 600                              |
| 2#            | 200                                      | 500                    | 700                              |
| 3#            | 300                                      | 500                    | 800                              |
| 4#            | 400                                      | 500                    | 900                              |

2) When the specified effective stress is reached, the acoustic tests of the triaxial specimens are performed as shown in Table 3.

| Sample Number | Effective Confining Pressure $\sigma'$ (kPa) | Excitation frequency $f$ (kHz) |
|---------------|------------------------------------------|------------------------------|
| 1#            | 100                                      | 45  100  200  250           |
| 2#            | 200                                      | 45  100  200  250           |
| 3#            | 300                                      | 45  100  200  250           |
| 4#            | 400                                      | 45  100  200  250           |

5.4. Test results and analysis
(1) Test results of sound attenuation
It can be seen from Figure 12, the P-wave acoustic attenuation of the sediment specimen is 70–220 dB/m. Under the same effective confining pressure, the P-wave sound attenuation rises with the increasing excitation frequency. However, under the same excitation frequency, the P-wave sound
attenuation decreases as the effective confining pressure increases. According to the law of conservation of energy, the increase of the excitation frequency leads to acceleration of the particle vibration in the triaxial specimen, the faster vibration of soil particles, and more wave energy is consumed. Based on the law of acoustic waves in solid, liquid, and gas, when the effective confining pressure increases, the fluid phase in pores of the triaxial specimen reduces, but the solid phase in a unit volume increases. Thus there is less wave energy to be consumed.

(2) Test results of sound velocity

It can be seen from Figure 13, the P-wave velocity of the triaxial specimen is 1650–1770 m/s. When the effective confining pressure is the same, the P-wave sound velocity increases with the increasing excitation frequency. Moreover, if the excitation frequency is the same, the P-wave velocity increases with the increase of the effective confining pressure. Due to the rising excitation frequency, the vibration speed of soil particles increases, the propagation time shortens, and the corresponding wave speed increases. When the effective stress increases, the volume of the triaxial specimen decreases, its stiffness increases, and the strain rebound time between the tensile and compression strain within an elastic range is shortened, so that the propagation velocity of the P-wave in the sediments is accelerated.

![Figure 12. P-wave attenuation of a triaxial sandy sediment specimen.](image1)

![Figure 13. P-wave velocity of a triaxial sandy sediment specimen.](image2)

From the above, the acoustic test results of triaxial specimens of sandy sediments are consistent with the existing laws of the acoustic characteristics of seabed sandy sediments [26,32,33]. Therefore, the developed measurement system can conduct acoustic tests on seabed sediments in the different initial effective stress states.

6. Conclusions

(1) By the GDS stress path triaxial system, a minimum axle-distance triaxial measurement system being suitable for the acoustic property measurement of seabed sediments is developed through adding a pair of P-wave transducers. The advantage of the equipment is not only simulate the complex stress states of seabed sediments, but also the acoustic attenuation and sound velocity can be measured.

(2) The measurement system is calibrated with the pure water test. The result shows that the difference between the two miniature hydrophone probes is small, the measurement accuracy is high, and the P-wave transducer has no obvious electromagnetic coupling phenomenon; the sound velocity and sound attenuation of pure water are consistent to the existing laboratory findings, which verifies the reliability of the developed acoustic measurement system.

(3) The acoustic test results of the triaxial specimens of sandy sediments in Hangzhou Bay are consistent with the existing theory of submarine sediments, indicating that the developed minimum axle-distance triaxial measurement system can be applied to study the acoustic characteristics of seabed sediments in a complex stress state.
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