Shear Wave Speed of Shallow Seafloor Sediments in the Northern South China Sea and Their Correlations With Physical Parameters

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Abstract In this study, shear wave speed and related physical properties were measured for 21 seafloor sediment cores collected in the northern South China Sea. Results reveal that the shear wave speed in this study area ranges between 15.57 and 75.55 m/s and demonstrates a pattern of regional distribution. The sediment in the continental shelf area shows characteristics of high shear wave speed, high wet bulk density, low porosity, and large grain size. Contrarily, the sediment in the continental slope area exhibits characteristics of low shear wave speed, low wet bulk density, high porosity, and fine particles. Accordingly, the correlation between shear wave speed and physical properties such as porosity, wet bulk density, water content, and average grain size was studied. Prediction formulas of shear wave speed of sediments in this study area containing single and double physical parameters were established via regression analysis. The comparison between single-parameter and double-parameter prediction formulas indicates that the determined coefficient of the double-parameter prediction formulas based on porosity and average grain size is higher than that of single-parameter prediction formulas. It indicates that the double-parameter prediction formulas based on porosity and average grain size have better prediction performance. Moreover, the prediction formulas established in this study were further compared with those of other study areas, and their differences were analyzed accordingly.

Plain Language Summary The shear wave speed of seafloor sediments is the velocity of shear wave propagating in seafloor sediments. Shear wave speed is one of the critical acoustic properties of seafloor sediments, which is very useful in many fields such as exploration and exploitation of seabed resources, precise prediction of the acoustic field, and prediction of stability with regard to engineering geology. In view of the importance of shear wave speed, the correlation between shear wave speed and physical properties such as porosity, wet bulk density, water content, and average grain size were analyzed, and the prediction formulas of shear wave speed were established in this study.

1. Introduction

Due to the rapid development of exploration and exploitation of seabed resources as well as the rapid growth in marine construction, the measurement and study of acoustic properties of seafloor sediments have received increasing attention (Hu et al., 2012; Song, 2007; Wang et al., 2006; Wen et al., 2006; Zheng et al., 2017). Shear wave speed is one of the critical parameters of the acoustic properties of seabed sediments, which has been extensively employed in various fields. For instance, shear wave speed is an essential input parameter for the acoustic models of the seabed, which is of great significance for accurate interpretation of seabed acoustic surveying data and precise prediction of the acoustic field of oceans (Buckingham, 2005; Lu et al., 2004). Besides, shear wave speed has fundamental applications in the evaluation and prediction of stability with regard to engineering geology, as well as other applications such as bearing capacity of foundation in seabed, shear strength of marine soil, and liquefaction of sand caused by an earthquake (Jackson & Richardson, 2007; Liu & Zhang, 2014).

There are several types of seafloor sediments in the northern South China Sea because of diverse material sources, making this area extremely suitable for studies of acoustic properties of seafloor sediments as
well as marine engineering geology. Presently, there are extensive and in-depth studies on the \( P \) wave speed and attenuation coefficient of sediments in this region, whereas shear wave speed is yet to be considered enough (Kan et al., 2012; Lu et al., 2005; Zou et al., 2009, 2018, 2019). Therefore, a study on the characteristics of the shear wave speed of sediments in this area can make up for the regional distribution limit of shear wave characteristic in shallow sediments and provide the basic data for the study and evaluation of the seafloor engineering geology in this area. Therefore, it has dual significance of both practical application and theoretical research.

Based on the measured data of shear wave speed and physical properties of sediment cores collected at 21 sites in the northern South China Sea, the correlation between shear wave speed and physical properties such as wet bulk density, water content, porosity, and average grain size were analyzed in this study. Further, we established prediction formulas containing single physical parameter and double physical parameters based on regression analysis between shear wave speed and the four parameters of physical properties mentioned above, which provide basic prediction formulas for the estimation of shear wave speed in this study area. Additionally, a comparison of the prediction formulas of shear wave speed versus physical properties of sediments established in this study and in other sea areas were conducted, and the difference and related reasons were analyzed.

2. Sample Source and Experimental Method

2.1. Study Area and Collection of Sediment Samples

The study area is located between 14°N to 20°N and 108°E to 115°E in the northern South China Sea. The submarine geomorphy of the study area includes the continental shelf and the continental slope. The sediments in continental shelf area are mainly composed of terrigenous clastic sediments, including gravelly sand, sand, clayey silt, and silty clay. The distribution characteristics of the sediments in the continental shelf are as follows. Gravelly sand is mainly distributed in the southern continental shelf area of the Pearl River Estuary, which is dominated by bioclastic sediments. Sand is primarily distributed on the continental shelf area east of 116°E with water depths of 50–200 m and has a characteristic coarsening gradually from west to east, while clay silt is distributed along a narrow and long belt paralleling a coastline. Silty clay is mainly distributed in the continental area west of the Pearl River Estuary with water depths of 50–200 m. The northern continental slope area of the South China Sea extends eastward across the northern area, with complex geomorphy and weak hydrodynamic conditions. The sediments in the continental slope area are mainly composed of silty clay, clayey silt, silt, and sand-silt-clay.

Twenty-one sediment cores were collected by using a gravity corer in the study area and packed in 110.0-mm-diameter PVC liner tubes. Five of them are located on the continental shelf area, and the other 16 are located on the continental slope area. The length of the longest and shortest cores among the 21 cores is 3 and 0.3 m, respectively. All the sediment cores were carried to and stored in a sample room with constant temperature and humidity after the survey cruise. For this study, every core was divided into sections with a length of 8 cm to measure shear wave speed and related physical properties in laboratory.

2.2. Measurement of Shear Wave Speed

Using the bender element system made by the Global Digital Systems Ltd, we measured the shear wave speed of sediment samples (see Figure 1a). The bender element system mainly consists of shear wave transducers, an integrated transmission and acquisition unit, and monitoring software. In order to improve the accuracy and efficiency of measurement, we customized a bracket for holding the shear wave transducer and sediment sample. The receiving transducer is fixed on the bottom of the bracket through a clamp, and the transmitting transducer is fixed on a vertically installed screw through a clamp. The height of the transmitting transducer can be adjusted by shaking the handle at the top of the bracket. There is a bender element stripe in each transducer, and it must be ensured that the stripes of transmitting and receiving transducers are in line, rather than perpendicular or crossed, when the receiving and transmitting transducers are positioned onto the sediment sample. After cutting the sample into 8-cm-long sections, we placed the sediment section onto the receiving transducer and adjusted the transmitting transducer onto one end of the sediment section by shaking the handle at the top of the bracket to ensure an efficient coupling between the bender stripes and the sediment. The formula for calculating shear wave speed using this method is as follows:
where $c_s$ is the shear wave speed of sediments in meters per second and $L$ is the length of the sample in meters, which can be measured by using a vernier caliper. The sample length is measured as follows: First, we ensured that the bender element stripes of the transmitting and receiving transducers were in direct contact with each other; then, we measured the distance between the transmitting and receiving transducer clamps without the sediment sample ($L_1$). Further, we measured the distance between the transmitting and receiving transducer clamps after placing the sample ($L_2$) and obtained the sampling length as follows: $L = L_2 - L_1$. In equation (1), $t$ is the propagation time of the shear wave in seconds and $t_0$ is the zero sonic time in seconds. Zero sonic time is a time delay of the bender element system, which is defined as the time difference.

Figure 1. (a) Photo of the bender element system and (b) waveform of shear wave at 1.5 kHz.
Table 1

Shear Wave Speeds of Different Types of Sediments Measured at Frequencies from 0.5 to 2 kHz

| Sediment type | Measuring frequency (kHz) | Shear wave speed (m/s) |
|---------------|--------------------------|------------------------|
| Silty clay    | 0.5–2                    | 15.57–45.10            |
| Clayey silt   | 0.5–2                    | 15.64–59.44            |
| Silty sand    | 0.5–2                    | 46.93–71.92            |
| Sandy silt    | 0.5–2                    | 59.59–75.55            |
| Clayey sand   | 0.5–2                    | 60.13–73.29            |
| Medium silt   | 0.5–2                    | 15.86–28.81            |
| Coarse silt   | 0.5–2                    | 20.57–55.66            |
| Sand-silt-clay| 0.5–2                    | 18.25–32.35            |

between transmitting and receiving shear waves when the stripes of transmitting and receiving transducers are directly docked without a sediment sample between them. In this study, the zero sonic time of the bender element system and the propagation time of the shear wave in the sediment were determined via the cross-correlation analysis of the transmitting and receiving shear wave signals, which avoids the calculation error of the propagation time caused by manually considering the first-break point of the shear wave. During the measurement of shear wave speed, the sampling frequency, sampling length, and excitation voltage were set as 1,000 kHz (i.e., the sampling interval is 1 μs), 10,000 sample points, and 14 V, respectively. The waveform of transmitting and receiving shear waves at 1.5 kHz is shown in Figure 1b. The measurement accuracy of the length of the sediment core and the travel time of the shear wave is ±0.1 mm and ±1 μs, respectively. So the accuracy of the shear wave speed of the bender element system was estimated to be better than ±0.2% for a typical sample with a length of 8 cm and shear wave speed of 60 m/s.

2.3. Measurement of Physical Properties

After the measurement of shear wave speed, we measured the physical properties of the sediment samples such as porosity, wet bulk density, water content, and average grain size and calculated the porosity of the sediment samples based on particle density and water content. The wet bulk density of samples was measured by using the ring knife method, and the water content was measured by using the drying method. Finally, we combined sieving and density meter analysis to measure the particle composition of samples.

3. Results

3.1. Result of Shear Wave Speed Measurement

In this study, eight different types of sediments, namely, silty clay, clayey silt, sandy silt, silty sand, clayey sand, coarse silt, medium silt, and sand-silt-clay, were chosen to measure shear wave speed. Table 1 shows the shear wave speeds for different types of the sediments at frequencies from 0.5 to 2.0 kHz. For one certain type of sediment, the boundary of the shear wave range in Table 1 indicates the minimum and maximum values of shear wave speed measured at frequencies from 0.5 to 2.0 kHz. Generally, the shear wave speeds of sediments in this study area ranged from 15.57 to 75.55 m/s, and the sediment types corresponding to the minimum and maximum shear wave speeds are silty clay and sandy silt, respectively. Table 1 indicates that the shear wave speeds of different types of sediments are quite different. According to Tables 1 and 2, the shear wave speeds of silty sand, sandy silt, and clayey sand with significantly high wet bulk density, low porosity, low water content, and large grain size were higher than those of sediments such as silty clay, clayey silt, medium silt, and sand-silt-clay, which have low wet bulk density, high porosity, high water content, and small grain size. The shear wave speed of sediments from the central South Yellow Sea (Kan et al., 2014), a tidal area in the Jiaozhou Bay (Zheng et al., 2015), the northern South China Sea (Pan et al., 2006), and the Florida Islands (Richardson et al., 1997) ranges from 12.05 to 74.55, from 26.5 to 103.5, from 29.2 to 128.3, and from 40.0 to 150.0 m/s, respectively. The shear wave speed measured in this study is comparable with those measured in the study area mentioned above as a whole. However, the maximum value of the shear

Table 2

Physical Properties of Different Types of Sediments

| Sediment type | Wet bulk density (g/cm³) | Porosity (%) | Water content (%) | Average grain size (Φ) |
|---------------|--------------------------|--------------|-------------------|------------------------|
| Silty clay    | 1.30–1.62                | 64.0–81.8    | 63.7–159.9        | 6.31–8.59              |
| Clayey silt   | 1.30–1.96                | 42.5–82.4    | 26.3–173.0        | 5.99–8.01              |
| Silty sand    | 1.86–1.94                | 43.3–49.5    | 26.8–38.2         | 4.18–5.19              |
| Sandy silt    | 1.81–1.96                | 43.1–50.5    | 27.5–35.4         | 4.89–5.66              |
| Clayey sand   | 1.80–1.96                | 42.4–52.5    | 26.1–40.4         | 4.29–4.86              |
| Medium silt   | 1.33–1.38                | 76.9–80.6    | 121.1–153.3       | 6.54–6.79              |
| Coarse silt   | 1.39–1.98                | 44.0–76.4    | 31.0–118.6        | 5.56–6.10              |
| Sand-silt-clay| 1.37–1.47                | 73.0–79.2    | 97.0–140.4        | 6.04–6.22              |
The wave speed measured in this study is slightly smaller than that obtained in previous studies, which shows that the physical properties of sediments have a significant impact on the acoustic properties of sediments. The difference of physical properties of sediments in different study areas accounts for the difference of sediment shear wave speeds measured in different study areas.

### 3.2. Result of Physical Property Measurement

Table 2 shows the physical properties of different types of sediments measured in this study. According to Table 2, considering the eight types of sediments as a whole, the wet bulk density, porosity, water content, and average grain size of sediments in this study area ranges from 1.30 to 1.98 g/cm³, from 42.4% to 82.4%, from 26.1% to 173.0%, and from 4.18Φ to 8.59Φ, respectively. Obviously, different types of sediments have different porosity, wet bulk density, water content, and average grain size. Sediments such as silty sand, sandy silt, and clayey sand have relatively high wet bulk density, low porosity, low water content, and large average grain size. Conversely, sediments such as silty clay, clayey silt, coarse silt, medium silt, and sand-silt-clay have relatively low wet bulk density, high porosity, high water content, and small average grain size.

### 4. Discussion

#### 4.1. Distribution of Shear Wave Speed

As mentioned above, there are two types of geomorphy: continental shelf area and continental slope area. Tables 3 and 4 show the results of the measurement of shear wave speed and physical parameters of different sediment types in continental shelf and continental slope areas, respectively. For one certain type of sediment, the boundary of the shear wave range in Tables 3 and 4 indicates the minimum and maximum values of shear wave speed measured at frequencies from 0.5 to 2.0 kHz. Comparison between Tables 3 and 4 indicates that the shear wave speed of sediments demonstrates a regional distribution characteristic along with corresponding physical properties. The sediments in the continental shelf are characterized by a relatively high shear wave speed, high wet bulk density, low porosity, and coarse grains. The shear wave speed ranges from 46.93 to 75.55 m/s, and the porosity ranges from 42.4% to 52.5%, the density ranges from 1.80 to 1.98 g/cm³, the water content ranges from 26.1% to 40.4%, and the average grain size ranges from 4.18Φ to 6.19Φ. Comparatively, the sediments in the slope area are characterized by a relatively low shear wave speed, low wet bulk density, high porosity, and fine particles; while the shear wave speed ranges from 16.86 and 45.10 m/s, the porosity ranges from 62.9% to 82.4%, the density ranges from 1.30 and 1.65 g/cm³, the water content ranges from 60.0% and 173.0%, and the average grain size ranges from 5.56Φ to 8.07Φ. As listed in Tables 3 and 4, the values of other physical parameters such as the wet bulk density, the porosity, and the water content are similar, except that the grain size of coarse silt is a little bit bigger than that of clayey silt. So the shear wave speed is similar between the clayey silt sediment and the coarse silt sediment.

### Table 3

Results of the Measurement of Shear Wave Speeds and Physical Parameters of Different Sediments in the Continental Shelf Area

| Sediment type     | Shear wave speed (m/s) | Wet bulk density (g/cm³) | Porosity (%) | Water content (%) | Average grain size (Φ) |
|-------------------|------------------------|--------------------------|--------------|-------------------|------------------------|
| Clayey silt       | 50.87–58.72            | 1.85–1.96                | 42.5–49.1    | 26.3–37.5         | 5.99–6.19              |
| Silty sand        | 46.93–71.92            | 1.86–1.94                | 43.3–49.5    | 26.8–38.2         | 4.18–5.19              |
| Sandy silt        | 59.59–75.55            | 1.81–1.96                | 43.1–50.5    | 27.5–35.4         | 4.89–5.66              |
| Clayey sand       | 51.46–73.29            | 1.80–1.96                | 42.4–52.5    | 26.1–40.4         | 4.29–4.89              |
| Coarse silt       | 51.45–55.66            | 1.98                     | 44.0         | 31.0              | 5.87                   |

### Table 4

Results of the Measurement of Shear Wave Speeds and Physical Parameters of Different Sediments in the Continental Slope Area

| Sediment type      | Shear wave speed (m/s) | Wet bulk density (g/cm³) | Porosity (%) | Water content (%) | Average grain size (Φ) |
|--------------------|------------------------|--------------------------|--------------|-------------------|------------------------|
| Silty clay         | 15.57–45.10            | 1.30–1.62                | 64.0–81.8    | 63.7–159.9        | 6.31–8.59              |
| Clayey silt        | 15.64–36.90            | 1.30–1.65                | 62.9–82.4    | 60.0–173.0        | 6.36–8.07              |
| Medium silt        | 16.86–28.81            | 1.33–1.38                | 76.9–80.6    | 121.1–153.3       | 6.54–6.79              |
| Coarse silt        | 21.57–23.00            | 1.39–1.41                | 75.6–76.4    | 113.2–118.6       | 5.56–6.10              |
| Sand-silt-clay     | 18.25–32.35            | 1.37–1.47                | 73.0–79.2    | 97.0–140.4        | 6.04–6.22              |
4.2. Correlation between Shear Wave Speed and Porosity

Porosity is the most fundamental factor affecting the acoustic properties of seafloor sediments. Hence, studying the correlation between porosity and the acoustic properties of sediments is essential. Figure 2 shows the correlation between shear wave speed measured at 1 kHz and porosity. As shown in Figure 2, the shear wave speed is negatively correlated with porosity; that is, it decreases with the increase of the porosity. Porosity is the ratio of fluid volume to total sediment volume in sediments. Shear wave can only propagate in the solid-phase medium of sediments but cannot propagate in the liquid-phase medium. Furthermore, porosity reflects the compactness of the sediment skeleton. The smaller the porosity of the sediment is, the larger the volume fraction of the solid-phase medium in the sediment, while the denser the sediment skeleton is, the larger the shear modulus of the sediment, which consequently is more conducive for the propagation of shear wave and also guarantees higher shear wave speed.

Through regression analysis of shear wave speed and porosity, single-parameter prediction formulas of shear wave speed at different frequencies based on sediment porosity were established, as shown in Table 5. Generally, shear wave speed has a good correlation with porosity, and the determined coefficients are greater than 0.78. Table 5 shows that despite some differences between the empirical regression formulas of shear wave speed versus porosity at different frequencies, the overall variation trend of shear wave speed versus porosity approximately exhibits a similar pattern. This is because the shear wave speed and physical parameters of sediments are inherent properties of seafloor sediments, whereas the prediction formula of shear wave speed was obtained via regression analysis, which also reflects the geoacoustic properties of sediments in the same sea area. The difference in the empirical regression formulas for the correlation between shear wave speed and porosity at different frequencies indicates that the shear wave speed in the study area possesses a dispersion characteristic although dispersion is not very significant.

The prediction formulas for predicting shear wave speed were established based on the data measured by different researchers in different research areas, such as the central South Yellow Sea (Kan et al., 2014), a tidal area in the Jiaozhou Bay (Zheng et al., 2015), and the Florida Bay (Richardson et al., 1997). The single-parameter prediction formula of shear wave speed based on porosity established in this study was compared with those from previous studies, and the result is shown in Figure 3. Figure 3 reveals that the shear wave speed predicted by the formula of Zheng et al. (2015) for tidal area sediments in the Jiaozhou Bay and that predicted by the formula of Richardson et al. (1997) for carbonate sediments in the Florida Bay were obviously higher than that obtained in this study. The shear wave speed predicted by the formula of Richardson et al. (1997) for siliceous sediments is slightly higher than that obtained in this study when the porosity range is between 40% and 50%, while it is lower than that measured in this study when the porosity range is between 60% and 85%. Additionally, the predicted shear wave speed from the formula of Kan et al. (2014) established in the central South Yellow Sea is lower than that obtained in this study in the porosity range of 40%–85%. The reason why the shear wave speed predicted by the formula of Richardson et al. establishes.
(1997) for carbonate sediments is higher than that predicted by the formula established in this study mainly lies in the different types of sediments and the different values of physical parameters that the formula is based on. In the formula of Richardson et al. (1997) for carbonate sediments, the high shear wave speed (>100 m/s) corresponds to the low porosity (mean value is lower than 45.0%) and large grain size (the $\Phi$ value of mean grain size is less than 1.3). Richardson et al. pointed out that the higher shear wave speeds relate to the high percentage of interparticle porosity, the higher grain bulk modulus, and the very poorly sorted nature of these carbonate sediments compared to those of siliciclastic sediments (Richardson et al., 1997). In the formula of Zheng et al. (2015), the water content of sediments from a tidal area in the Jiaozhou Bay was very low, ranging from 23.2% to 40.7%. This may lead to the formula of Zheng et al. (2015) predicting a higher shear wave speed. The formula of Kan et al. (2014) was established mainly based on the data of sediments with relatively low shear wave speed such as silty clay and clayey silt. In this study, the regression formula was based on the data including both the sediments with low shear wave speed such as silty clay and clayey silt and the sediments with relatively high shear wave speed such as silty sand, sandy silt, and clayey sand. This may lead to the difference of shear wave prediction between the formula of Kan et al. (2014) and the formula established in this study.

4.3. Correlation Between Shear Wave Speed and Wet Bulk Density

Figure 4 shows the correlation between shear wave speed at 1 kHz and wet bulk density. Through regression analysis of shear wave speed versus wet bulk density, the single-parameter prediction formula of shear wave speed at different frequencies based on wet bulk density of sediments was established, as shown in Table 6. In general, shear wave speed is positively correlated with wet bulk density, with a determined coefficient of prediction formulas greater than 0.76. According to its geotechnical definition, wet bulk density is the quality of sediment per unit volume, which is related to sediment material composition, specific gravity of soil particles, pore volume, and amount of pore water. Thus, the wet bulk density comprehensively reflects the material composition and structural characteristics of sediments. In addition, it reflects the compactness of the sediment skeleton. The higher the wet bulk density, the denser the skeleton, and the more conducive the propagation of shear wave in the sediment, the greater the shear wave speed.

The prediction curves of shear wave speed from the wet bulk density-based formulas established by different researchers in different study areas and those established in this study as well as the measured data of shear wave speed obtained in this study are presented together in Figure 5. Results shown in Figure 5 clearly indicate that the predicted value of shear wave speed established by Pan et al. (2006) is close to the shear wave
speed obtained herein when the wet bulk density is within the range of 1.30–1.50 g/cm³. The predicted results from the formula of Richardson et al. (1997) for siliceous sediments are also close to the shear wave speed obtained in this study when the wet bulk density is within the range of 1.55–1.65 g/cm³, while the predicted results from the carbonate sediment prediction formula (Richardson et al., 1997) are significantly higher than the shear wave speed obtained herein. In terms of wet bulk density, when it was within the range of 1.20–2.00 g/cm³, the trend of the prediction curve of the prediction formula established by Kan et al. (2014) is almost the same as that of the prediction formula established in this study. However, the predicted shear wave speed value from the formula of Kan et al. (2014) was lower than that from the prediction formula in this study.

4.4. Correlation Between Shear Wave Speed and Water Content

Figure 6 shows the correlation between shear wave speed at 1 kHz and water content. Based on regression analysis of shear wave speed and water content, single-parameter prediction formulas of shear wave speed based on water content in sediments at different frequencies were established, as shown in Table 7. Figure 6 clearly reveals that shear wave speed is negatively correlated with water content; that is, with the increase of water content, shear wave speed decreases. Water content of sediments refers to the ratio of the volume of the liquid-phase medium to that of the solid-phase medium in sediments. Furthermore, water content, as well as porosity, is employed to characterize the volume characteristics of the solid and liquid phases in sediments. The smaller the water content, the smaller the volume of the liquid-phase medium, and the higher

![Figure 4. Shear wave speed versus wet bulk density at a frequency of 1 kHz.](image_url)

| Frequency (kHz) | Single-parameter prediction formula | Determined coefficient $R^2$ |
|----------------|-------------------------------------|-----------------------------|
| 0.5            | $c_s = 60.95410\rho^2 - 140.1400\rho + 102.3350$ | 0.768                       |
| 0.6            | $c_s = 62.87869\rho^2 - 145.2249\rho + 105.8092$ | 0.769                       |
| 0.7            | $c_s = 63.88140\rho^2 - 148.2006\rho + 108.0999$ | 0.769                       |
| 0.8            | $c_s = 64.92005\rho^2 - 150.4293\rho + 109.3510$ | 0.765                       |
| 0.9            | $c_s = 65.40060\rho^2 - 151.5900\rho + 110.2071$ | 0.764                       |
| 1.0            | $c_s = 69.06819\rho^2 - 162.1296\rho + 117.8852$ | 0.764                       |
| 1.5            | $c_s = 72.93691\rho^2 - 172.9834\rho + 125.6872$ | 0.768                       |
the relative density of the solid-phase matter, the denser the sediment as well as the higher the shear wave speed.

The prediction curves of shear wave speed from water content-based formulas established by different researchers in different study areas and formulas in this study and the measured data of shear wave speed are presented together in Figure 7. Figure 7 shows that the predicted values of shear wave speed from water content-based prediction formulas of Pan et al. (2006) are higher than the measured shear wave speed.
obtained in this study within the water content range of 20%–80%. The predicted value of shear wave speed from the formula of Kan et al. (2014) is lower than that obtained in this study when the water content is in the range of 20%–130% but is higher within the water content range of 130%–180%.

4.5. Correlation Between Shear Wave Speed and Average Grain Size

Figure 8 shows the correlation between shear wave speed at a frequency of 1 kHz and average grain size. Through regression analysis of shear wave speed and average grain size at different frequencies, single-parameter prediction formulas of shear wave speed at different frequencies based on average grain size of sediments were established, as shown in Table 8. Figure 8 indicates that shear wave speed is negatively correlated with the value of $\Phi$ for average grain size; that is, with the increase of the value of $\Phi$, shear wave speed decreases. However, according to the definition of average grain size in the unit of $\Phi$, the larger the value of $\Phi$, the smaller the sediment particles. Therefore, the shear wave speed of sediments actually decreases with a decrease in grain size. Regarding the determined coefficient, the correlation between the shear wave speed and average grain size of sediments is relatively poor, and the determined coefficient is less than that of the empirical regression formulas of the parameters such as the wet bulk density, porosity, and water content. Average grain size is one of the feature parameters for characterizing the properties of sediment particles. The correlation between shear wave speed and sediment particle properties is often affected by several factors. In addition to the average grain size of sediments, particle size sorting, particle shape,
particle arrangement, and other factors have a certain impact on the shear wave speed of sediments. Therefore, the shear wave speed of sediments may differ greatly even if the average grain size of sediments is the same. Moreover, for a given size of argillaceous sediments, consolidation (drainage) experiments can reduce porosity and increase the density of sediments without changing the average size of sediments, thus increasing the shear wave speed. Thus, it partly explains the reason for the poor correlation between shear wave speed and average grain size and indicates that average grain size is not a good descriptor of shear wave speed.

Richardson et al. (1997) discussed the correlation between in situ shear wave speed and average grain size of siliceous and carbonate sediments in the Florida Bay and established the single-parameter prediction formulas of shear wave speed based on average grain size for siliceous sediments and carbonate sediments, respectively. The predicted shear wave speed from the prediction formulas of Richardson et al. was compared with the measured shear wave speed in this study and that predicted by the formula based on average grain size established herein. The result is shown in Figure 9, and it shows that the results from the prediction formulas of Richardson et al. for both siliceous and carbonate sediments are obviously higher than those obtained in this study when the average grain size is within the range of $4\Phi$–$9\Phi$. Moreover, the result of Richardson et al. is much higher than the result from the prediction formula established in this study within the average grain size range of $4\Phi$–$9\Phi$.

Generally, there are apparent differences between the predicted shear wave speed from the prediction formulas established by other researchers according to the data from different study areas and that from

![Figure 8. Shear wave speed versus average grain size at a frequency of 1 kHz.](image)

**Table 8**

| Frequency (kHz) | Single-parameter prediction formula | Determined coefficient $R^2$ |
|-----------------|-------------------------------------|-------------------------------|
| 0.5             | $c_s = 3.09076M_z^2 - 48.6283M_z + 216.4276$ | 0.645                         |
| 0.6             | $c_s = 3.18688M_z^2 - 50.0663M_z + 221.9284$ | 0.651                         |
| 0.7             | $c_s = 3.19592M_z^2 - 50.2259M_z + 222.7134$ | 0.651                         |
| 0.8             | $c_s = 3.24510M_z^2 - 51.0868M_z + 226.3515$ | 0.649                         |
| 0.9             | $c_s = 3.22325M_z^2 - 50.8654M_z + 226.3078$ | 0.649                         |
| 1.0             | $c_s = 3.33434M_z^2 - 52.5736M_z + 232.9609$ | 0.658                         |
| 1.5             | $c_s = 3.43804M_z^2 - 54.1888M_z + 239.4341$ | 0.664                         |
prediction formula established in this study. The reasons may mainly lie within two aspects. The first is due
to the difference of data from different research areas on which the prediction formulas were based. The dif-
ferent sedimentary environment, ocean current, and material source of sediments in different research areas
usually lead to different types of seafloor sediments. Moreover, sediments may have different values of phy-
sical parameters such as porosity, wet bulk density, water content, compressibility, shearing strength even
though the type of sediment is the same, which is defined according to marine geological standards, because
of the specific sediment environment in different areas. All of these may bring in the difference of the shear
wave speed and physical properties of sediments, leading to the difference in the regression formulas of
shear wave speed versus physical properties. The second reason is due to the differences in the method of
measuring the shear wave speed. The prediction formulas of Richardson et al. (1997) are based on the in situ
shear wave speed of sediments, while the prediction formulas established by Zheng et al. (2015), Kan et al.
(2014), and Pan et al. (2006) were based on the shear wave speed obtained in the laboratory by using the
Geotechnical Digital Systems bender element system. Moreover, the measuring frequency that different
researchers used to measure the shear wave speed is not the same. The prediction formula of shear wave
speed based on single or double sediment physical parameters in a research area may not be applicable to
the prediction of shear wave speed in another sea area. Therefore, investigators must be extremely careful
in choosing the prediction formulas to estimate shear wave speed of sediments, and they need to ensure that
the prediction formula is suitable for the selected study area. That is the purpose of making comparisons
among different prediction formulas.

4.6. Double-Parameter Prediction Formula of Shear Wave Speed Versus Physical Properties

The single-parameter prediction formula of shear wave speed can reflect the variation trend of shear wave
speed along with only one particular parameter of physical properties in seafloor sediments. However, a sin-
gle parameter of physical properties can only describe one aspect of the characteristics of sediments, and not
the comprehensive characteristics. Therefore, any single-parameter prediction formula of shear wave speed
cannot adequately characterize the effect of other physical parameters upon shear wave speed except the
related regression parameter. Among the four physical parameters having relatively good correlation with
shear wave speed in this study, porosity is the most critical factor that affects the shear wave speed of
sediments. As the parameters representing the bulk properties of sediments, the wet bulk density, water content, and porosity are highly correlated with each other. However, grain size is a parameter reflecting the property for the grain size component of sediments, which is relatively independent of wet bulk density, water content, and porosity. Therefore, the porosity and average grain size were chosen as regression analysis parameters to establish the double-parameter prediction formulas of shear wave speed of seabed sediments in the study. Figure 10 shows the three-dimensional correlation of shear wave speed with both porosity and average grain size. The result indicates that the predicted value of shear wave speed from the double-parameter prediction formula with regard to both porosity and average grain size fits considerably well with the shear wave speed measured in this study area. Table 9 shows the double-parameter prediction formulas of shear wave speed based on porosity and average grain size and the corresponding determination coefficients ($R^2$) at different frequencies. The determined coefficients of the double-parameter prediction formulas in Table 9 are generally higher than those of the single-parameter prediction formulas established in this study, which indicates that the double-parameter prediction formulas based on porosity and average grain size are efficient in estimating the shear wave speed of seabed sediments in this study area.

**Figure 10.** Shear wave speed versus porosity and average grain size at a frequency of 1 kHz.

**Table 9**

| Frequency (kHz) | Double-parameter prediction formula | Determined coefficient $R^2$ |
|----------------|------------------------------------|-----------------------------|
| 0.5            | $c_s = -0.0193\beta^2 - 1.9632\beta - 1.3379M_z^2 - 6.9819M_z + 0.4658\beta M_z + 137.621$ | 0.816                       |
| 0.6            | $c_s = -0.0195\beta^2 - 1.9191\beta - 1.3555M_z^2 - 8.038M_z + 0.4711\beta M_z + 153.3924$ | 0.817                       |
| 0.7            | $c_s = -0.0187\beta^2 - 1.893\beta - 1.4135M_z^2 - 7.909M_z + 0.4641\beta M_z + 144.1857$ | 0.816                       |
| 0.8            | $c_s = -0.0193\beta^2 - 1.9379\beta - 1.4226M_z^2 - 8.1101M_z + 0.4746\beta M_z + 153.39243$ | 0.813                       |
| 0.9            | $c_s = -0.0187\beta^2 - 1.9957\beta - 1.4767M_z^2 - 7.568M_z + 0.4698\beta M_z + 146.836$ | 0.812                       |
| 1.0            | $c_s = -0.0193\beta^2 - 1.941\beta - 1.4694M_z^2 - 9.0325M_z + 0.4852\beta M_z + 153.3924$ | 0.815                       |
| 1.5            | $c_s = -0.0196\beta^2 - 1.9737\beta - 1.5639M_z^2 - 9.6554M_z + 0.4991\beta M_z + 159.0235$ | 0.819                       |
5. Conclusions

1. The distribution of shear wave speed and physical properties of sediments in the study area has regional characteristics. The sediment in the continental shelf area shows a characteristic of relatively high shear wave speed, high wet bulk density, low porosity, and coarser grains. Comparative ly, the sediment in the continental slope area shows a characteristic of low shear wave speed, low wet bulk density, high porosity, and fine grains.

2. The shear wave speed in the study area was found to be positively correlated with wet bulk density and negatively correlated with porosity, water content, and the Φ value of average grain size. Among the four parameters of sediment physical properties mentioned above, the correlation between shear wave speed and porosity is the best and the corresponding determined coefficient is highest with a value greater than 0.78. Conversely, the correlation between shear wave speed and average grain size is lowest, with the smallest determined coefficient of less than 0.66. For a given regression parameter, the variation trend of shear wave speed at different frequencies was basically the same, but the determined coefficients of prediction formulas slightly differ, indicating that the shear wave speed in the study area has certain dispersion characteristic.

3. Through regression analysis, single-parameter and double-parameter prediction formulas of the shear wave speed of seabed sediments were established in this study area, which can be used to predict the shear wave of sediments in this area. Compared with the single-parameter prediction formula, the double-parameter prediction formula based on porosity and average grain size has a higher determined coefficient, indicating the double-parameter prediction formula based on porosity and average grain size has a better prediction result. Comparison between the shear wave speed measured in this study and the prediction result from the prediction formulas established in another study area indicates that there are some differences between the measured shear wave speed and the prediction result. Therefore, caution must be taken when predicting shear wave speed by using the formulas established in different study areas.

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