

Article

Dynamic Analysis of Subsea Sediment Engineering Properties Based on Long-Term In Situ Observations in the Offshore Area of Qingdao

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Abstract: The drastic changes in the marine environment can induce the instability of seabed sediments, threatening the safety of marine engineering facilities such as offshore oil platforms, oil pipelines, and submarine optical cables. Due to the lack of long-term in situ observation equipment for the engineering properties of seabed sediments, most existing studies have focused on phenomena such as the erosion suspension of the seabed boundary layer and wave-induced liquefaction, leading to insufficient understanding of the dynamic processes affecting the seabed environment. In this study, a long-term in situ observation system for subsea engineering geological environments was developed and deployed for 36 days of continuous monitoring in the offshore area of Qingdao. It was found that wave action significantly altered sediment mechanical properties, with a 5% sound velocity increase correlating to 39% lower compression, 7% higher cohesion, 11% greater internal friction angle, and 50% reduced excess pore water pressure at 1.0–1.8 m depth, suggesting sustained 2.2 m wave loads of expelled pore water, driving dynamic mechanical property variations in seabed sediments. This long-term in situ observation lays the foundation for the monitoring and early warning of marine engineering geological disasters.

Keywords: long-term in situ observation; offshore seabed sediments of Qingdao; acoustic/resistivity/excess pore pressure of sediment; sediment physical and mechanical properties; natural marine disasters



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1. Introduction

The shallow marine hydrodynamic environment is governed by diverse forces—including waves, tides, and storm surges—that drive sediment transport through bedload migration, suspended advection, and mass movements, posing global risks to subsea infrastructure [1]. Among these, wave action is particularly significant due to its short periodicity and high frequency, making it the dominant hydrodynamic force in shallow seas [2]. Under such intense hydrodynamic conditions, the seabed experiences processes such as erosion, sediment resuspension and deposition [3], liquefaction, debris flow, shear deformation, and submarine landslides [4], all of which pose serious threats to the safety of offshore drilling

platforms, subsea pipelines, and optical cables [5]. These processes represent critical risk factors for marine engineering and are urgent issues that need to be addressed in national marine development [6]. The occurrence and development of seabed geological disasters lead to significant changes in the engineering geological properties of seabed sediments [7]. Therefore, conducting long-term in situ observations of dynamic changes in seabed engineering geological parameters is essential for understanding the dynamic behavior of sediment properties. This research will help reveal the mechanisms behind the formation and evolution of seabed geological disasters, providing valuable insights for preventing such disasters and safeguarding the construction of marine engineering projects.

Recent studies on dynamic changes in shallow marine engineering geological environments primarily focus on long-term in situ observations, with an emphasis on wave-induced seabed erosion, resuspension, and liquefaction. In 1967, the NGI-UI pore water pressure sensor, jointly developed by the Norwegian Geotechnical Institute (NGI) and the University of Illinois (UI), was successfully applied in a geological survey of the Wilkinson Basin at a water depth of 278 m [8,9]. Subsequently, Bennett et al. [10] conducted an 8-month long-term observation at the Mississippi River Delta using composite pressure sensors, measuring dynamic changes in pore water pressure under wave action. In the 1980s, a joint Sino-American investigation deployed pore water pressure sensors in the underwater delta region of the Yellow River, capturing pore water pressure variations during three storm surge events [11], lacking multi-parameter and long-period observational verification ([12]). Liu [13] developed an in situ pore water pressure monitoring device for seabed soils, capable of measuring excess pore water pressure at different soil depths up to 15 m below the mud line. A research team led by Professor Jia developed a series of in situ long-term monitoring technologies and equipment for seabed engineering environments, covering areas from shallow coastal zones to deep offshore regions, revealing the dynamic changes in the seabed boundary layer [14]. The Piezometer series equipment, developed by the French Institute for Research and Exploitation of the Sea (Ifremer), is capable of operating at water depths up to 6000 m [15]. In 2006, Yang et al. [16] conducted a 7-day in situ observation in the tidal flat area of Jiaozhou Bay, using ADP-XR and OBS-3A to measure seabed horizontal flow characteristics, backscatter intensity, and suspended sediment concentration, revealing the variation patterns and controlling factors of suspended sediment concentration, which showed a U-shaped trend during each tidal cycle. In the same year, Ma [17] conducted a 5-month in situ observation in the Beibu Gulf region, utilizing a monitoring platform consisting of ADCP, PC-ADP, OBS, an inclinometer, and fan-shaped sonar to acquire continuous wave data, turbulence data, flow profiles, seabed morphology images, and the suspended sediment concentration.

In 2015, Zhang [18] conducted a 4-month in situ observation experiment in the underwater delta of the Yellow River, quantitatively revealing the contribution of wave-induced transient liquefaction and residual liquefaction to sediment erosion and resuspension. In 2021, Feng [19], based on long-term in situ observation data and laboratory experiments, used a deep learning model combining Long Short-Term Memory (LSTM) networks to predict and analyze 3.5-day transient pumping resuspension. Wen [20] conducted a 24-day in situ observation in the Chengdao Sea area of the Yellow River underwater delta, successfully capturing seven storm wave events. This study investigated the changes in the structure of near-bottom suspended sediments and the interaction between bottom seawater, the seabed interface, and shallow sediments under varying dynamic marine conditions.

Shallow marine sediments undergo dramatic physical and mechanical property changes due to external geological forces such as ocean currents, waves, and tides. However, existing in situ long-term observations primarily focus on wave-induced seabed erosion, resuspension, and liquefaction, with limited research on the dynamic changes in

the physical and mechanical properties of seabed sediments. Resistivity measurements, as an important means in modern marine geophysical research, can analyze the changes in the engineering geological properties of seafloor sediments with high sensitivity [21]. In recent years, the seafloor resistivity measurement method has become an effective indirect method for in situ soil physical property testing [22] and long-term observation [23]. Through the analysis of the observed resistivity data, the physical state and changes in seafloor sediments can be obtained [24]. Acoustic measurement is an effective indirect method for the non-destructive long-term observation of the changes in the mechanical properties of seafloor sediments. By establishing the internal connection between the acoustic parameters of seafloor sediments and the engineering mechanical characteristics of sediments, the in situ observation of the structure and engineering properties of seafloor sediments can be achieved [25]. The mechanical properties of seafloor sediments cover a lot of aspects. At present, the basic parameters that have attracted widespread attention include compression modulus, shear strength, cohesion, and internal friction angle [26].

Since a single geophysical measurement data point has multiple interpretations, it is impossible to accurately judge the physical and mechanical state of sediments using only one of the acoustic or electrical methods. To address this gap, a newly developed in situ monitoring system for seabed engineering geological environments was deployed for a 36-day long-term observation in the shallow seas off Qingdao. The 36-day observation period can cover two complete spring-neap tide cycles (14.75 days) and record the wave event triggering (such as wave loading) and the lagged response of sediments (such as the accumulation release cycle of pore water pressure). This study revealed the temporal variation patterns of seabed water, sediment resistivity, acoustic parameters, and excess pore water pressure, contributing valuable insights into the dynamic changes in seabed sediments.

2. Study Area

The study area was located at Caodao Island (Figure 1), managed by the Qingdao National Deep Sea Center. This island is situated in a semi-enclosed bay within a temperate maritime zone, influenced by the East Asian monsoon and the South Yellow Sea water mass system. The region experiences a temperate monsoon climate, with an average annual temperature of 12.3 °C. During the autumn and winter, northwesterly winds prevail, while southeasterly winds dominate in spring and summer.

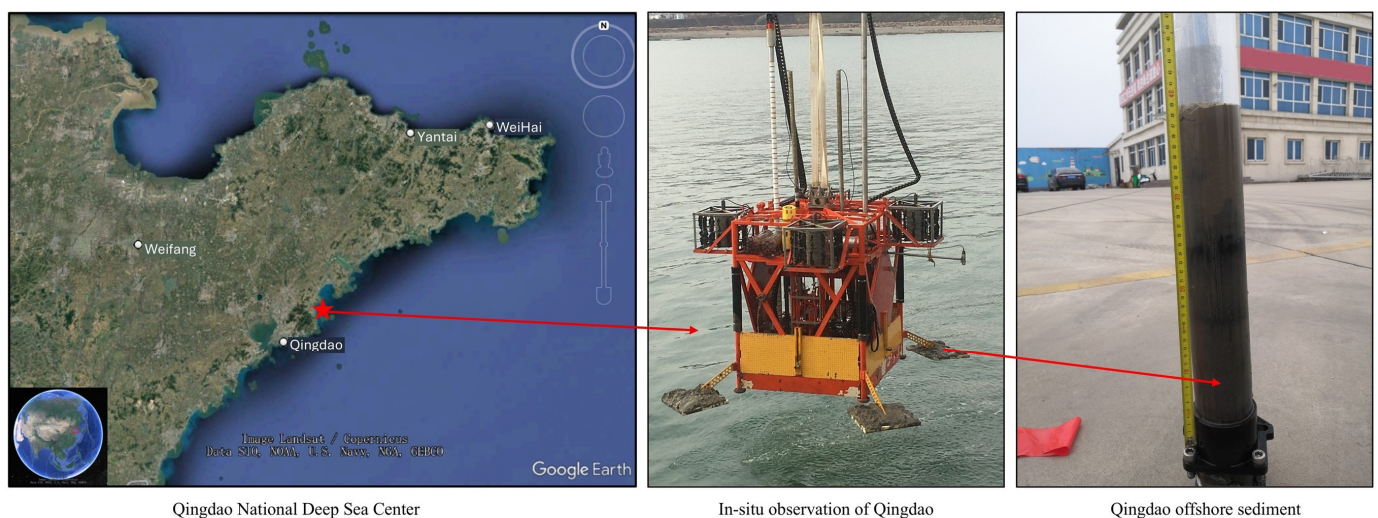


Figure 1. In situ observation sites and columnar sediment samples off the coast of Qingdao.

The study area is characterized by a semi-diurnal tidal regime, with water currents reaching speeds of up to 180 cm/s. The bay exhibits complex circulation patterns, with multiple circulation systems contributing to the intricate hydrodynamics of the region. The water depth in the area is approximately 15 m, and the overlying sediments consist of low-permeability silts and fine sands, ranging from 3 to 5 m in thickness. The density is 1.13–1.23 g/cm³, water content is 102.7–109.5%, plasticity index is 32.60–76.30, and liquid index is 1.50–3.22 [27]. Therefore, this sediment is vulnerable to wave liquefaction. Meanwhile, the topography of the Yellow Sea continental shelf leads to enhanced wave refraction (with an annual average effective wave height of 1.5–2.5 m), providing a natural experimental site for studying the dynamic response of wave-induced sediments (such as pore water migration and shear strength changes).

The ecological environment of the study area is shaped by both natural processes and human activities, making it a representative site for studying the effects of wave action on the dynamic changes in the engineering geological properties of seabed sediments.

3. Method

The observations in this study were conducted using an in situ long-term monitoring system for subsea engineering geological environments, which was independently developed by our team [14]. This system employs various methods, including acoustic, resistivity, and excess pore water pressure measurements, to monitor the dynamic changes in the physical and mechanical properties of seabed sediments.

The system primarily consists of the following components: an acoustic profile monitoring system, a high-precision seabed resistivity monitoring system, an excess pore water pressure monitoring system, an oceanic environmental monitoring system, a data acquisition and real-time transmission system, and a long-term power supply system. The core of the monitoring system focuses on the long-term observation of changes in the resistivity, acoustic properties, and excess pore water pressure of the seabed sediments (Figure 2), thereby capturing dynamic variations in the physical and mechanical properties of the seabed. The high-precision observation module for the resistivity of seabed sediments adopts the pseudo-random coding emission of electrical signals and characteristic signal recognition technology, realizing the nano-volt level observation of the deep-sea electric field and achieving a resistivity measurement accuracy of 5‰. The multi-channel acoustic section observation technology on the seabed utilizes the long-term transmission technology of high-frequency acoustic signals under the high-pressure environment in the deep sea and the multi-channel acoustic section scanning technology to achieve the construction of multi-channel sound fields on the seabed and high-resolution acoustic section observations. The high-resolution observation module for pore water in seafloor sediments based on the fiber-optic differential pressure structure adopts the deep-sea differential pressure fiber of Bragg grating excess pore water pressure sensing and ultra-high hydrostatic pressure self-balancing technology, realizing the accurate measurement of the excess pore water pressure of sediments in the deep-sea environment (with a measuring range of 500 kPa and an accuracy of 0.1 kPa).

The communication and control system enables bidirectional communication and data transmission between the seabed, the sea surface, and the shore. The power supply system, which utilizes a uniquely designed seawater battery, can meet the system's energy requirements for continuous operation over a year on the seabed.

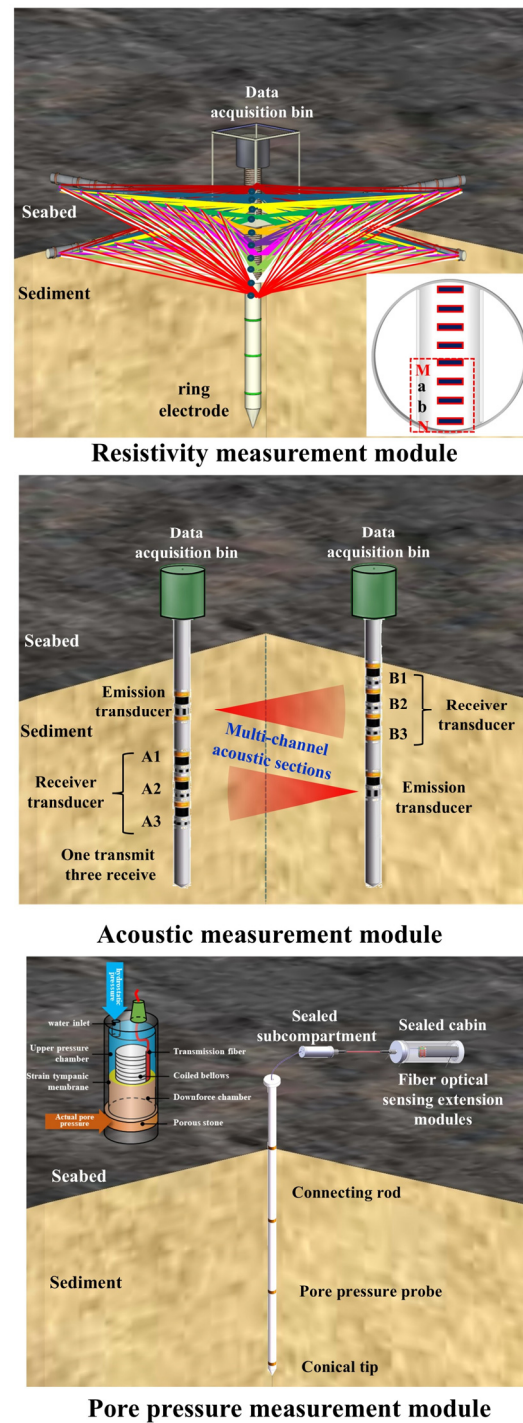


Figure 2. Improved resistivity acoustic pore pressure measurement sensor and measurement scheme (Symmetrical Four-Electrode: Four electrodes are arranged in a straight line in sequence as A-M-N-B. A and B are current electrodes used for injecting current; M and N are potential electrodes used for measuring potential difference; A1/A2/A3, B1/B2/B3 are the receiving electrodes of the A and B probes respectively; The same is below).

This monitoring equipment (Figure 3) has undergone multiple nearshore sea trials and has been successfully deployed aboard research vessels, including Haiyang Geological No. 6, Dongfanghong III, and Zhang Jian, for deep-sea tests in the South China Sea. The results of these trials have been stable, accurate, and reliable [28].

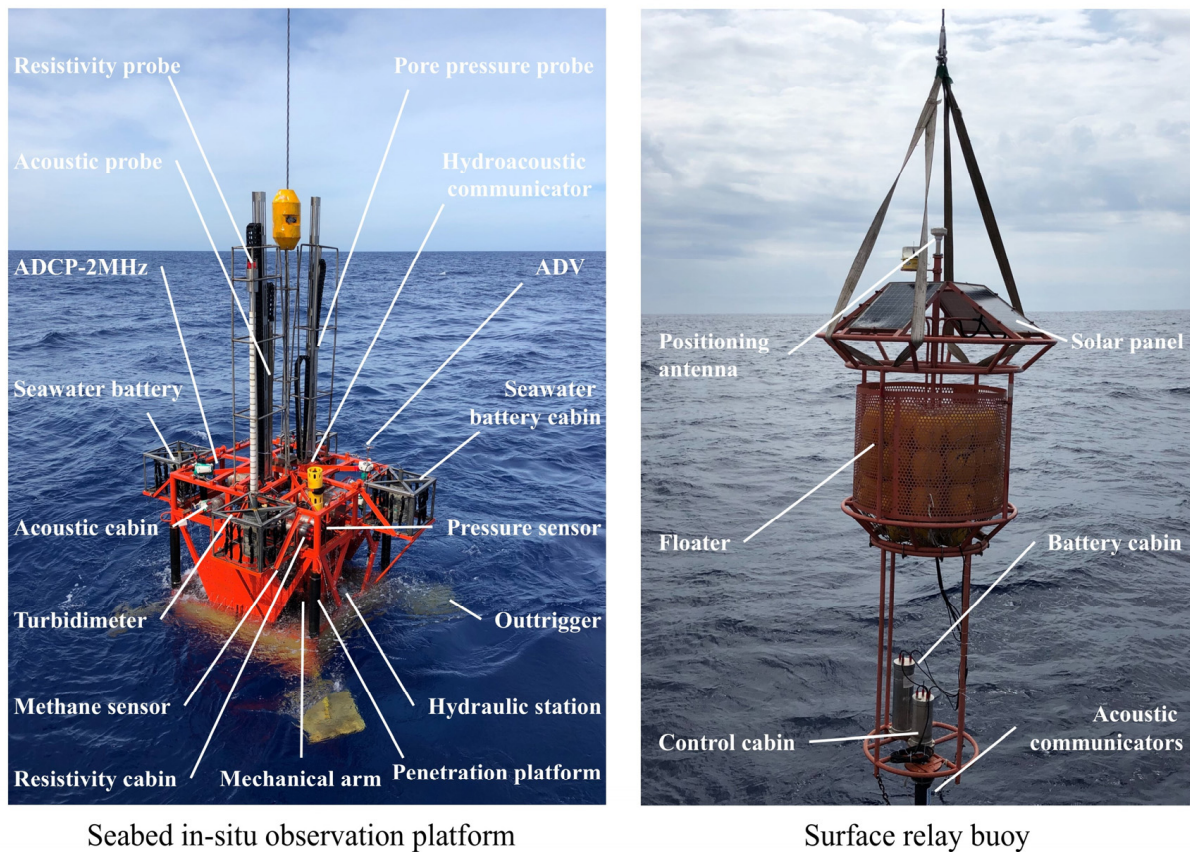


Figure 3. In situ long-term monitoring system for subsea engineering geological environments. The seabed in situ observation platform (**left**) is used to acquire seafloor sediment data and store the data; the surface relay buoy (**right**) receives seabed survey data via underwater acoustic communication and transmits them to the lab via satellite, modified from [28].

In November 2019, a 36-day in situ long-term observation of the seabed engineering geological environment was conducted in the offshore area of Qingdao using the independently developed subsea engineering geological environment monitoring system (Figure 4). The observation platform was equipped with a vertical resistivity probe, two acoustic probes, and an excess pore water pressure probe.

The resistivity probe, which is 4.5 m long, consists of 60 electrode rings spaced 6.5 cm apart, with measurements taken using the Wenner method in a rolling configuration. The acoustic measurement system is divided into two groups, each consisting of one transmitter transducer and three receiver transducers. During operation, the transmitter emits sound waves, while the three receivers capture the waves. The two groups alternate between transmitting and receiving acoustic signals. The excess pore water pressure probe is 5 m long and is equipped with four fiber-optic Bragg grating sensors, each separated by 1 m, to measure differential pressure.

During the observation, the probes were sequentially driven into the seabed sediments to a depth of 1.6 m. It can cover the engineering geological risk layers within the burial depth range of submarine pipelines. The system measured the resistivity, acoustic properties, and excess pore water pressure of the seabed sediments every 2 h over 36 days. These measurements allowed for the acquisition of vertical distribution profiles and dynamic variation patterns of the resistivity, sound speed, and excess pore water pressure in the seabed water and sediments.

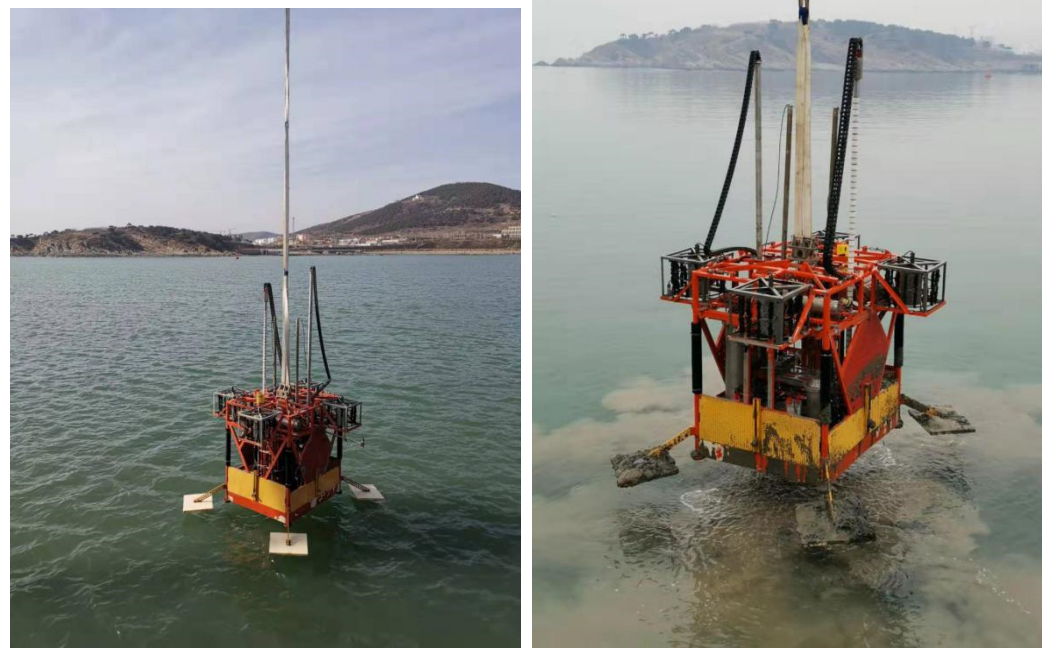


Figure 4. In situ observation of the engineering geological environment of Qingdao shallow seabed (the photo on the (left) was taken when the in situ seafloor observation platform was deployed, and the photo on the (right) was taken when the in situ seafloor observation platform was retrieved).

4. Results

4.1. Characteristics of the Offshore Water Environment in Qingdao

Under varying sea conditions, the extent and structure of the seabed boundary layer undergo dynamic changes. These changes in the boundary layer contribute to geological hazards such as the erosion, deposition, resuspension, transport, disturbance, and disruption of shallow sediments, and even landslides or instability in the seabed. This study conducted a 36-day observation of the dynamic changes in seabed sediments under different sea conditions. During the observation period, there were two instances when the wave height exceeded 1 m and five instances when the wave height was greater than 0.5 m. During the observation period, no waves or tide gauges were installed, so there were no wave height data. Therefore, the data from the adjacent observation stations were used instead. It can be seen from the figure that there are a total of three observation stations near the seafloor observation location. Among them, the Wheat Island Observatory Station is the closest to the observation location, and the absolute distance between them is very short. Hence, the wave height data of the Wheat Island Observatory Station can be approximately regarded as the wave height data of the seafloor observation point (Figure 5). The first event occurred from 11 November to 13 November, lasting for 2 days with a maximum wave height of 1 m. The second event lasted from 16 November to 20 November for 4 days, with a maximum wave height of 2.2 m. The third event took place from 26 November to 27 November, with a maximum wave height of 0.6 m. The fourth event occurred from December 1 to December 2, lasting 2 days with a maximum wave height of 0.5 m. The fifth event took place from 12 December to 14 December, lasting 2 days, with a maximum wave height of 0.6 m.

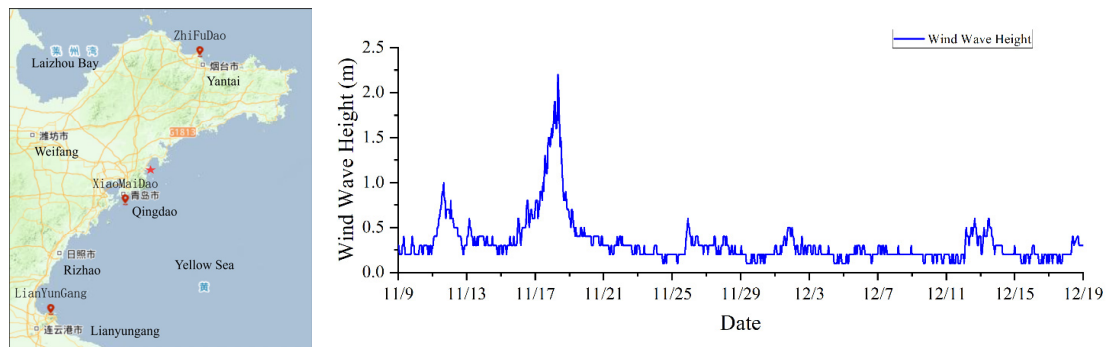


Figure 5. Wind wave height data during shallow sea observation. The (left) picture shows the wave observation locations during the shallow sea observation period. Among them, the red five-pointed star indicates the location of seafloor observation, and the balloons represent the adjacent observation stations. The (right) picture shows the wave height data during the observation period. Source: National Marine Science Data Center—Wheat Island Observatory.

4.2. In Situ Subsea Resistivity Observation Results

The resistivity monitoring of the subsea environment includes measurements of seawater, the seabed boundary layer, and shallow sediments. The ranges of resistivity changes observed in these areas were as follows: seawater resistivity varied from 0.08 to 0.14 $\Omega\cdot\text{m}$; the seabed boundary layer resistivity ranged from 0.07 to 0.24 $\Omega\cdot\text{m}$; and the resistivity of the sediments fluctuated between 0.01 and 0.24 $\Omega\cdot\text{m}$ (Figure 6).

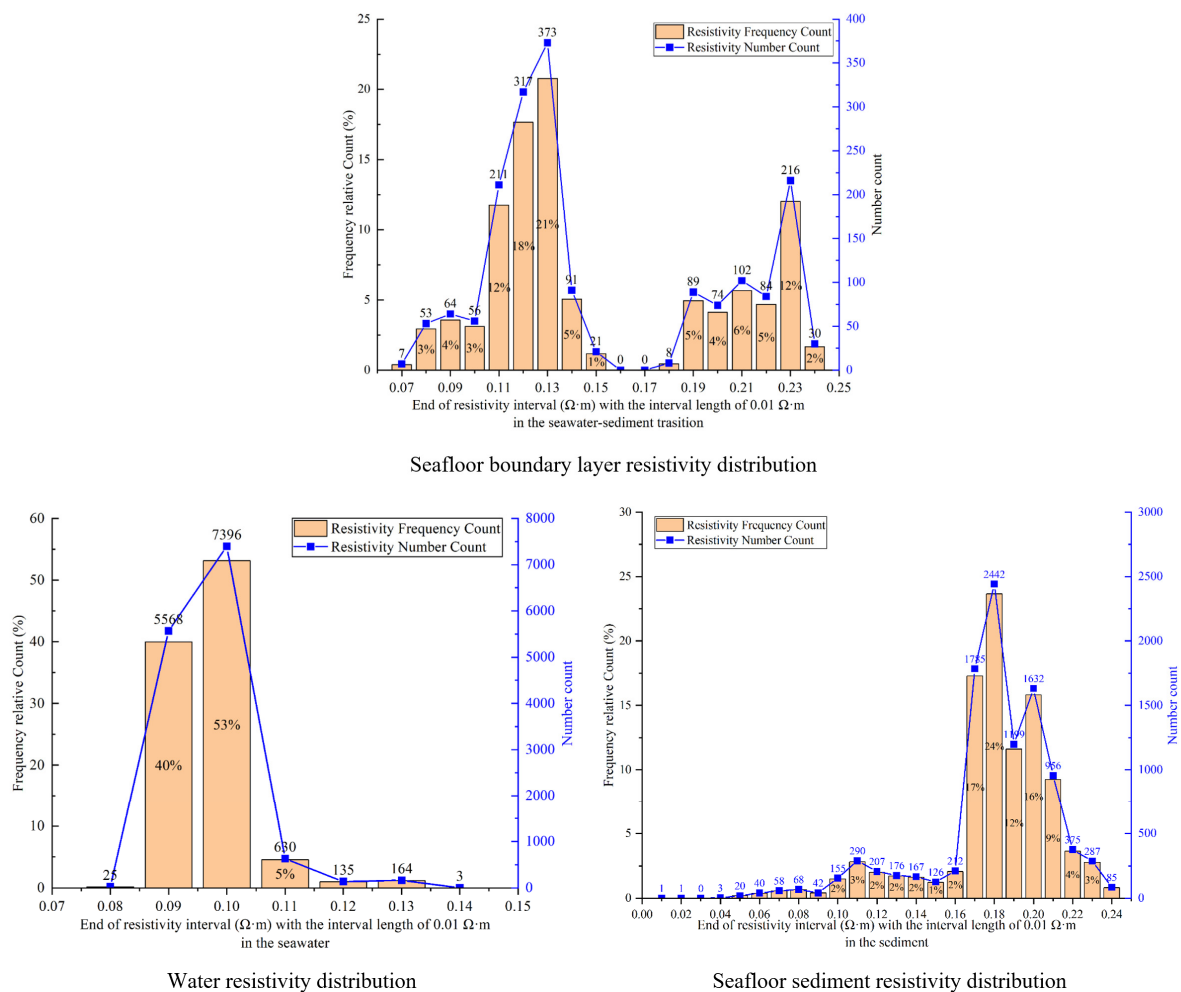


Figure 6. Resistivity distribution in seawater, seabed boundary layer, and sediments.

4.2.1. Vertical Spatial Structure of Seabed Resistivity

The vertical spatial structure of seabed resistivity can be divided into three parts: seawater resistivity, seabed boundary layer resistivity, and sediment resistivity (Figure 7). To illustrate, the vertical resistivity profile on November 9 shows a resistivity range from 0.05 to 0.20 $\Omega\cdot\text{m}$.

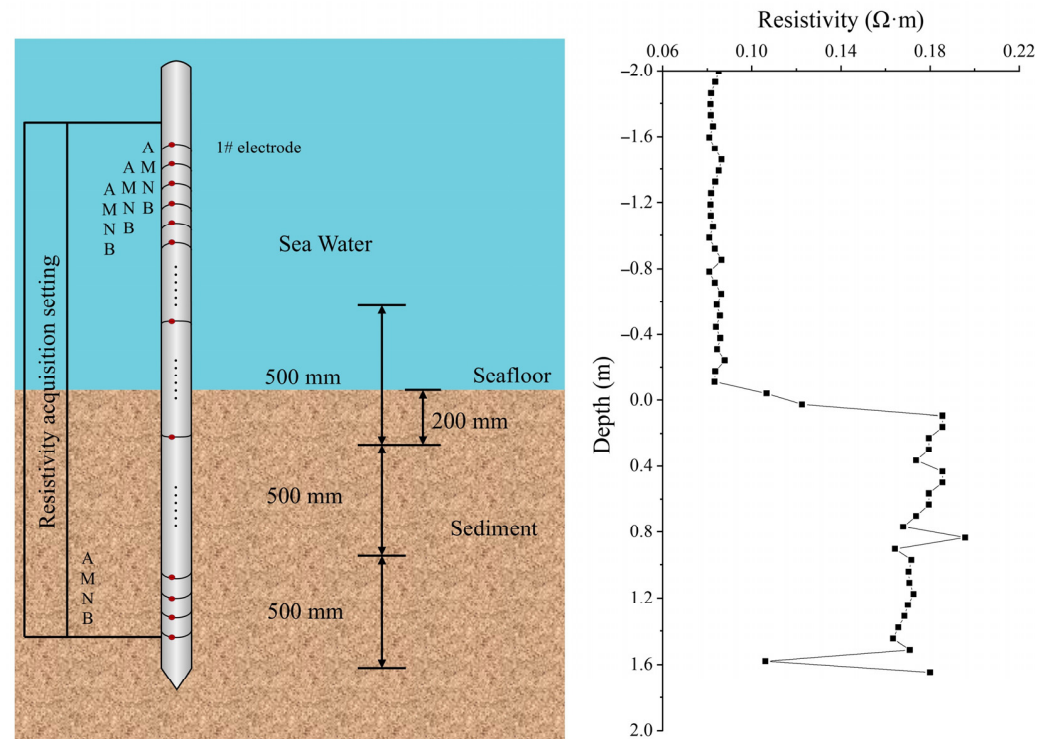


Figure 7. Schematic diagram of seafloor resistivity measurement and measurement results (1# means the 1st electrode).

Seawater Resistivity: Measured up to 2.09 m above the seabed, seawater resistivity ranged from 0.07 to 0.08 $\Omega\cdot\text{m}$, with a change of 0.01 $\Omega\cdot\text{m}$. The small variation in vertical resistivity indicates good consistency in electrode measurements and suggests that the seawater is relatively homogeneous in the vertical direction.

Seabed Boundary Layer Resistivity: Measured in the 0.2 m range near the seabed, resistivity ranged from 0.07 to 0.18 $\Omega\cdot\text{m}$, with a change of 0.11 $\Omega\cdot\text{m}$. This measurement involved four electrodes, and the resistivity was measured using the four-electrode Wenner method, with two outer electrodes supplying current and two inner electrodes measuring the potential. As the measurement probes moved downward, the resistivity increased due to the resistivity contrast between the water and sediment. When all four electrodes were within the sediment, the measured resistivity reflected the true resistivity of the seabed sediment.

Sediment Resistivity: Measured between 0.09 and 1.64 m below the seabed, the resistivity varied from 0.05 to 0.19 $\Omega\cdot\text{m}$, with a change of 0.14 $\Omega\cdot\text{m}$. Resistivity generally decreased with depth, though two significant anomalies were observed. The first anomaly occurred at a depth of 0.83 m, where resistivity abruptly increased from 0.16 $\Omega\cdot\text{m}$ to 0.19 $\Omega\cdot\text{m}$, a change of 0.03 $\Omega\cdot\text{m}$. This increase indicates a change in sediment properties, leading to a higher resistivity state. The second anomaly appeared at 1.58 m, where resistivity abruptly decreased from 0.16 $\Omega\cdot\text{m}$ to 0.05 $\Omega\cdot\text{m}$, a decrease of 0.11 $\Omega\cdot\text{m}$. This drop, approaching the resistivity of seawater, suggests the potential presence of a high-salinity fluid migration pathway in this area.

4.2.2. Temporal Variation in Seabed Resistivity

The seabed resistivity measurements were conducted from 9 November 2019 to 14 December 2019, for a total of 36 days.

The resistivity of seawater showed a consistent overall trend (Figure 8). For example, at a depth of 1.05 m above the seabed, the seawater resistivity increased from $0.08 \Omega \cdot \text{m}$ to $0.10 \Omega \cdot \text{m}$, a change of $0.02 \Omega \cdot \text{m}$, with a slight upward trend over time. The seawater resistivity can be divided into three distinct periods:

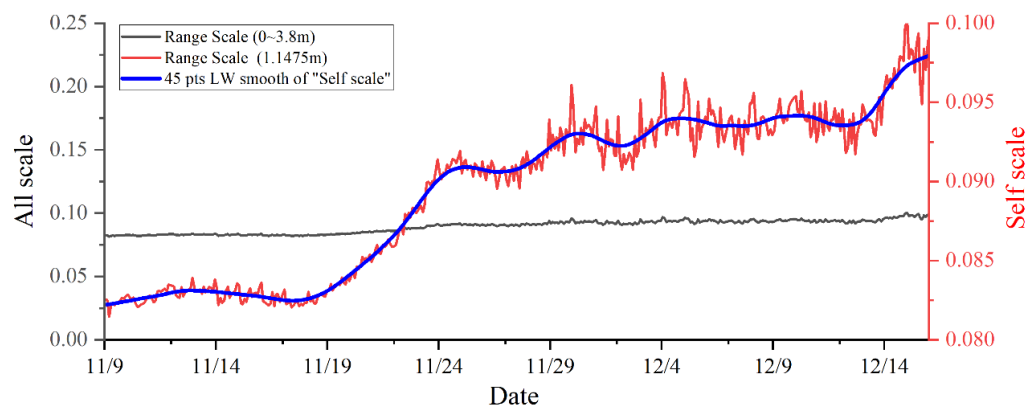


Figure 8. Resistivity curve in seawater over time (“45 pts LW” means each of the 45 points was subjected to smoothing fitting using “the Locally Weighted Scatterplot Smoothing” method).

Period 1 (9 November–19 November): The resistivity remained relatively constant at around $0.08 \Omega \cdot \text{m}$.

Period 2 (19 November–24 November): The resistivity increased linearly from $0.083 \Omega \cdot \text{m}$ to $0.091 \Omega \cdot \text{m}$, a 10% increase.

Period 3 (24 November–16 December): The resistivity showed a fluctuating increase, rising from $0.091 \Omega \cdot \text{m}$ to $0.11 \Omega \cdot \text{m}$.

The seabed boundary layer resistivity was measured over the same period as the seawater (Figure 9). During this time, the resistivity of the boundary layer increased from $0.12 \Omega \cdot \text{m}$ to $0.21 \Omega \cdot \text{m}$, a change of $0.09 \Omega \cdot \text{m}$. The temporal variation in seabed boundary layer resistivity can be divided into four periods:

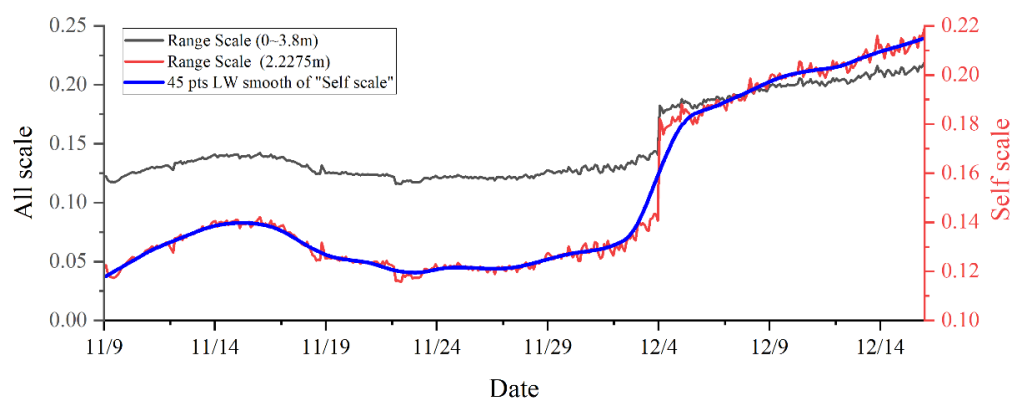


Figure 9. The curve of seafloor boundary layer resistivity over time (“45 pts LW smooth” refers to Figure 8).

Period 1 (9 November–22 November): The resistivity first increased, and then decreased, rising from $0.12 \Omega \cdot \text{m}$ to $0.14 \Omega \cdot \text{m}$, before dropping to $0.11 \Omega \cdot \text{m}$.

Period 2 (22 November–4 December): The resistivity gradually increased from $0.11 \Omega \cdot \text{m}$ to $0.14 \Omega \cdot \text{m}$.

Period 3 (4 December 11:24–13:24): A sharp increase in resistivity occurred, from $0.14 \Omega \cdot \text{m}$ to $0.18 \Omega \cdot \text{m}$.

Period 4 (4 December 13:24–16 December): The resistivity continued to increase gradually, from $0.18 \Omega \cdot \text{m}$ to $0.21 \Omega \cdot \text{m}$.

The temporal variation in the seabed boundary layer resistivity reflects the dynamic process of sediment erosion, deposition, and resuspension at the seabed.

Seabed sediment resistivity at different depths showed varying trends over time. At a depth of 1.04 m below the seabed, the sediment resistivity first decreased and then increased, divided into two periods (Figure 10):

Period 1 (9 November–13 November): The resistivity decreased from $0.17 \Omega \cdot \text{m}$ to $0.16 \Omega \cdot \text{m}$.

Period 2 (13 November–16 December): The resistivity steadily increased from $0.16 \Omega \cdot \text{m}$ to $0.17 \Omega \cdot \text{m}$.

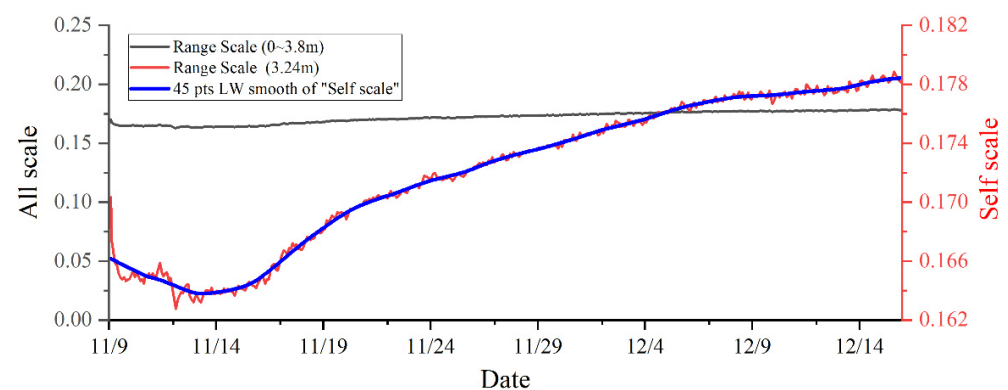


Figure 10. The variation in sediment resistivity with time at the depth of 1.04 m below the seabed (“45 pts LW smooth” refers to Figure 8). At a depth of 1.38 m below the seabed, the resistivity initially increased, then decreased, with the following three periods (Figure 11).

Period 1 (9 November–22 November): The resistivity increased steadily with minor fluctuations, from $0.09 \Omega \cdot \text{m}$ to $0.10 \Omega \cdot \text{m}$.

Period 2 (22 November–27 November): The resistivity increased sharply from $0.10 \Omega \cdot \text{m}$ to $0.15 \Omega \cdot \text{m}$.

Period 3 (27 November–16 December): The resistivity gradually decreased, from $0.15 \Omega \cdot \text{m}$ to $0.11 \Omega \cdot \text{m}$.

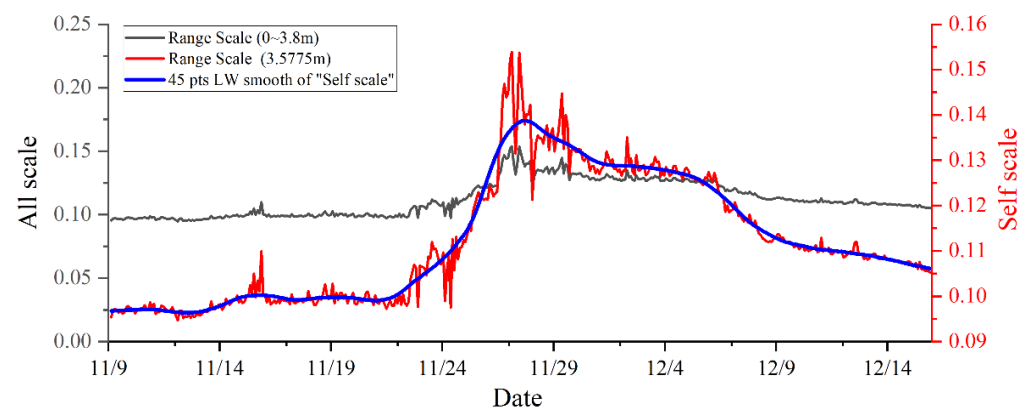


Figure 11. The variation in sediment resistivity with time at the depth of 1.38 m below the seabed (“45 pts LW smooth” refers to Figure 8).

4.3. Seabed Sound Velocity Observation Results

The vertical spatial distribution of the seabed sound velocity indicates that sound velocity increases gradually with depth (Table 1), exhibiting some fluctuations (Figure 12). For example, on November 9, the sound velocity in seawater was 1529 m/s. At a depth of 0.3 m below the seabed, the sediment sound velocity increased to 1610 m/s. At a depth of 0.6 m, the sound velocity slightly decreased to 1598 m/s. As the depth increased to 0.8 m below the seabed, the sediment sound velocity rose to 1713 m/s. At a depth of 1.3 m, the sound velocity slightly decreased to 1710 m/s but then increased again to 1786 m/s at 1.6 m.

Table 1. Summary of six channels of sound velocity of seafloor sediments.

Receiving Channel	Depth (m)	Min (m/s)	Max (m/s)	Average (m/s)	RMSE	Standard Deviation
CH1	0	1516	1571	1540	74	9
CH2	0.3	1558	1774	1569	321	18
CH3	0.6	1563	1885	1580	521	23
CH4	1.0	1557	1864	1810	594	24
CH5	1.3	1565	1823	1767	442	21
CH6	1.6	1561	1917	1845	5818	76

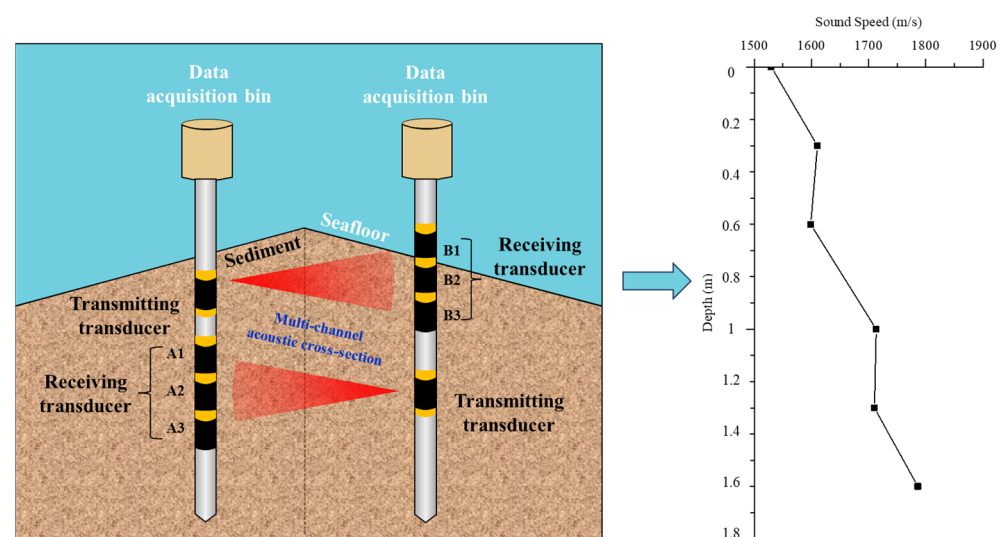


Figure 12. Illustration of seabed sound velocity measurements and vertical spatial distribution of sound velocity.

Temporal Variation in Seabed Sound Velocity at Different Depths

Seabed sound velocity at different depths exhibited varying temporal changes (Figure 13).

In seawater above the seabed: The sound velocity fluctuated slightly over time, with a variation range from 1516 to 1571 m/s. The average sound velocity was 1540 m/s, with a variance of 74 and a standard deviation of 9.

At 0.3 m below the seabed: The sediment sound velocity decreased slightly over time by about 50 m/s. The variation range was from 1558 to 1774 m/s, with an average of 1569 m/s, a variance of 321, and a standard deviation of 18.

At 0.6 m below the seabed: The sediment sound velocity fluctuated slightly, with a variation range from 1563 to 1885 m/s. The average sound velocity was 1580 m/s, with a variance of 521 and a standard deviation of 23.

At 1.0 m below the seabed: The sediment sound velocity showed greater fluctuations in the initial period, becoming more stable in the later period. The variation range was from 1557 to 1864 m/s, with an average of 1810 m/s, a variance of 594, and a standard deviation of 24.

At 1.3 m below the seabed: The sediment sound velocity remained relatively stable in the initial period, but fluctuated more in the later period, with an increase of approximately 90 m/s, representing a 5% increase. The variation range was from 1565 to 1823 m/s, with an average of 1767 m/s, a variance of 442, and a standard deviation of 21.

At 1.6 m below the seabed: The sediment sound velocity was stable in the early period, and then increased by about 100 m/s in the later period, followed by fluctuations. The variation range was from 1561 to 1917 m/s, with an average of 1845 m/s, a variance of 5818, and a standard deviation of 76.

On 12 November, at noon, changes in sediment sound velocity were observed in all but the 0.6 m depth channel. Specifically, the following were observed:

At 0.3 m below the seabed, the sediment sound velocity decreased.

At the seabed, and at depths of 1, 1.3, and 1.6 m below the seabed, the sound velocity increased to varying degrees.

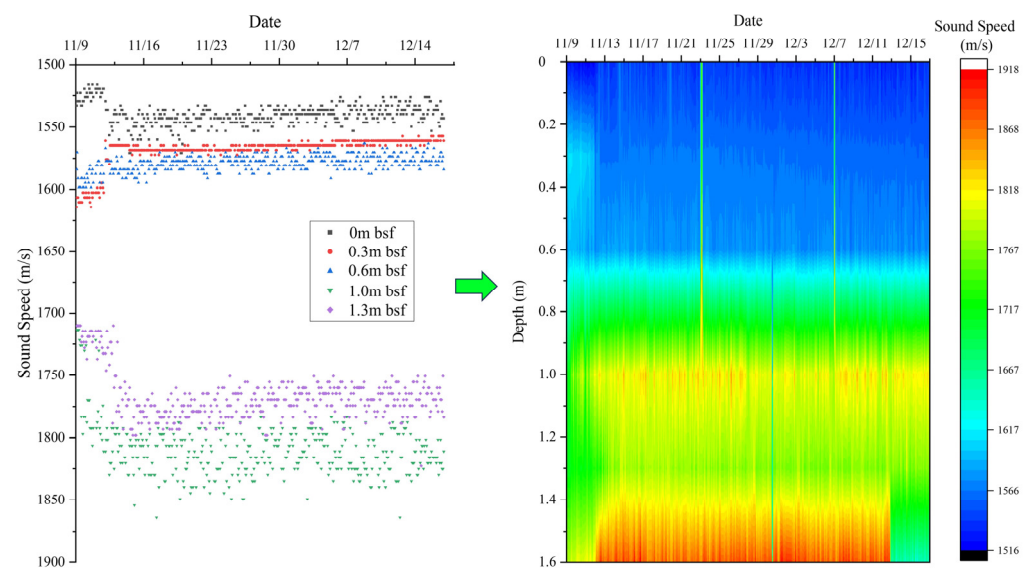


Figure 13. Spatial and temporal distribution of submarine sound velocity with cloud and scatter graphs.

4.4. Seabed Pore Pressure Observation Results

Sediment pore pressure sensors were installed at depths of 0.6 m and 1.6 m below the seabed to measure the excess pore water pressure (Figure 14).

At a depth of 0.6 m below the seabed, the excess pore pressure in the sediment remained relatively stable, with minimal variation.

At a depth of 1.6 m below the seabed, the excess pore pressure in the sediment initially decreased and then increased. The changes can be divided into four distinct stages:

Stage 1 (15–21 November): The excess pore pressure slightly increased, from 5.32 kPa to 5.68 kPa, an increase of 7%.

Stage 2 (21–25 November): The excess pore pressure rapidly decreased, dropping from 5.68 kPa to 2.48 kPa, a decrease of 56%.

Stage 3 (25 November–6 December): The excess pore pressure gradually decreased, from 2.48 kPa to 1.64 kPa, a decrease of 34%.

Stage 4 (6–18 December): The excess pore pressure gradually increased again, rising from 1.64 kPa to 2.79 kPa, an increase of 70%.

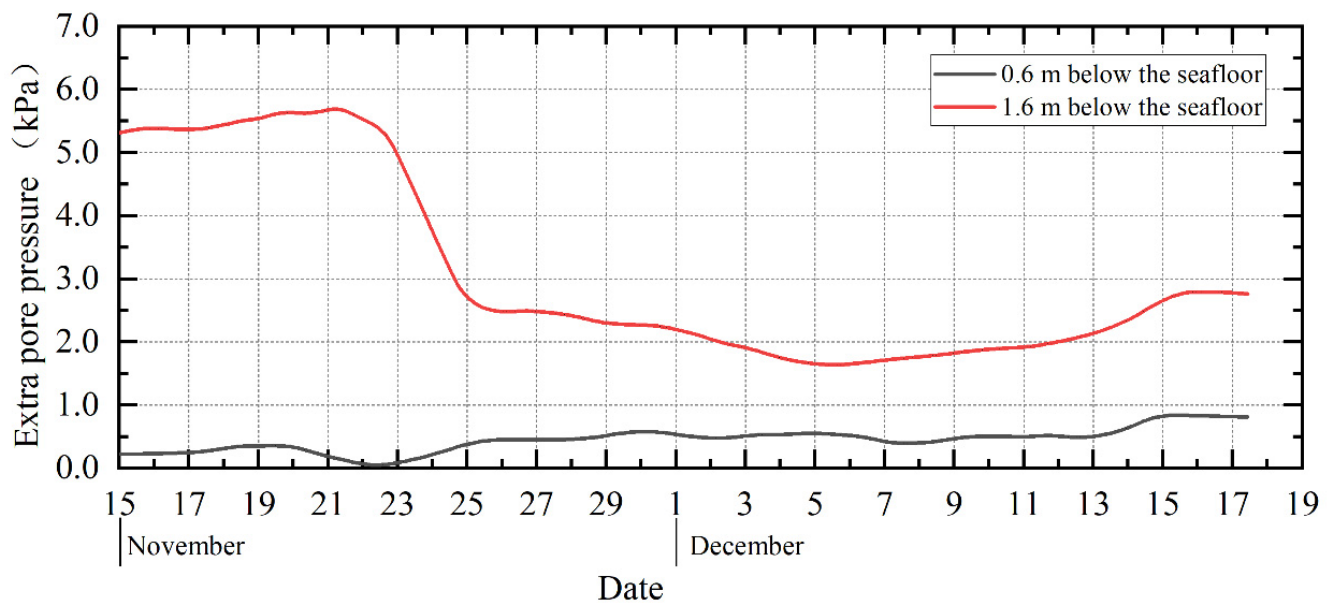


Figure 14. Variation curve of excess pore water pressure with time.

5. Analysis of Dynamic Changes in Seabed Sediments off the Coast of Qingdao

5.1. Inversion Model of Acoustic and Electrical Parameters and Physical and Mechanical Properties of Sediments

We measured many submarine sediment samples. With data from the literature and the Keras module in Python 3, we constructed a single-input (resistivity) and multi-output (density, water content, and porosity) model with a six-layer dense neural network. The training was carried out 180 times with the best prediction robustness, and five-fold model validation was adopted. Compared with the traditional empirical model, the prediction accuracy of this model improved by 33%, and the accuracy of the prediction range increased by 50%. The correlations between resistivity and the physical properties of the seabed manifested as follows: the resistivity gradually increases with the increase in density; the resistivity gradually decreases with the increase in porosity; and the resistivity gradually decreases with the increase in water content (Figure 15).

The sound velocity of the sediment was the most correlated with the compression coefficient, followed by the internal friction angle and cohesion (Figure 16). The sound velocity of sediment and the compression coefficient showed an exponential functional relationship. The sound velocity of the sediment is a parabolic function with the cohesion and internal friction angle.

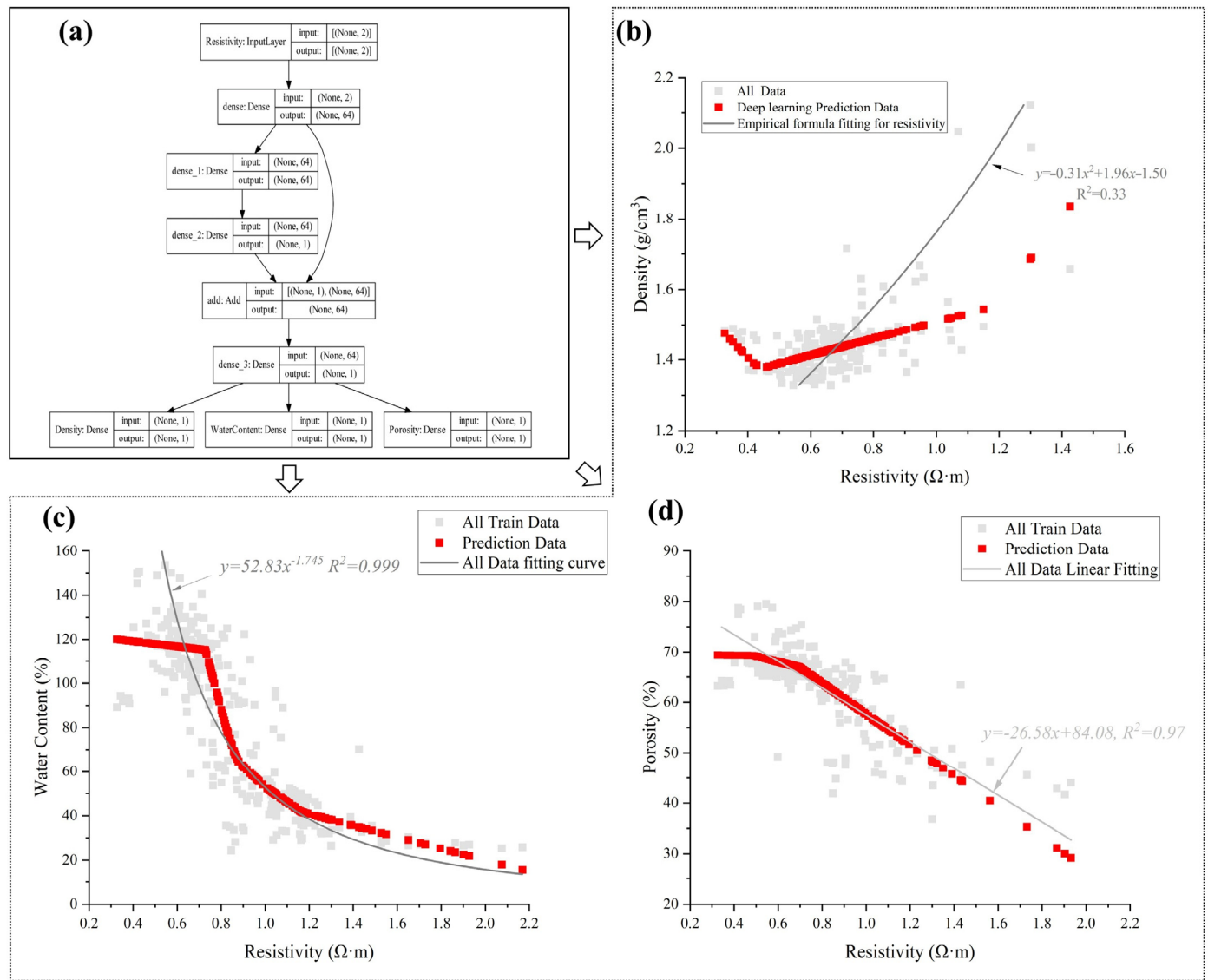


Figure 15. Construction algorithm and prediction model of seafloor sediment resistivity and density, water content and porosity ((a) is the framework of the deep learning neural network model based on the resistivity inversion of the seafloor sediment density, water content, and porosity; (b–d) show the relationship between resistivity and density/water content/porosity based on an empirical equation and deep learning model (modified from [29])).

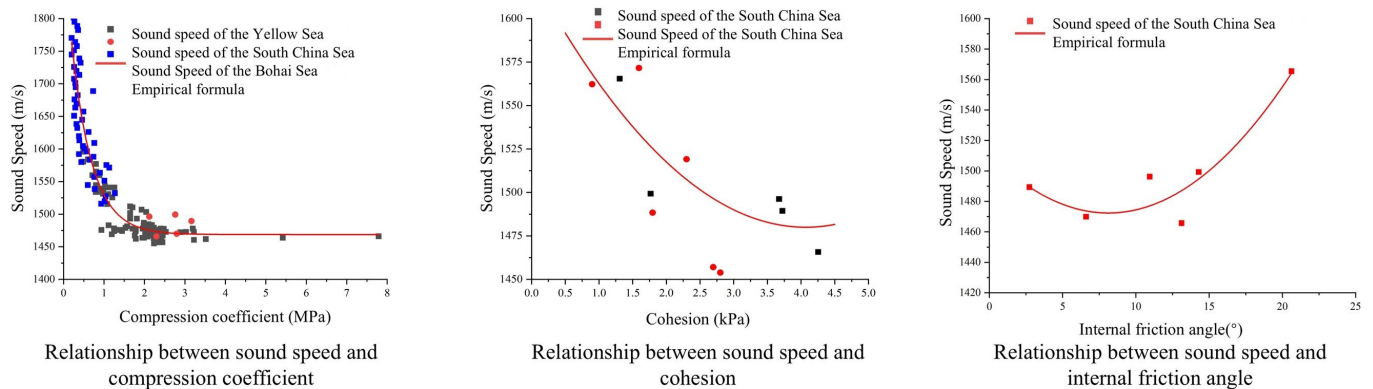


Figure 16. The relationship between the sound speed, compression coefficient, cohesion, and internal friction angle (Data source: Yellow Sea [30], South China Sea [25,29] Bohai Sea [31]).

5.2. Dynamic Variation in Seabed Physical Properties in the Qingdao Offshore Area

Based on the relationship between seabed sediment resistivity and physical properties previously established by the author [29], the dynamic variations in sediment density, water content, and porosity in the Qingdao offshore seabed have been inferred from resistivity measurements (Figure 17).

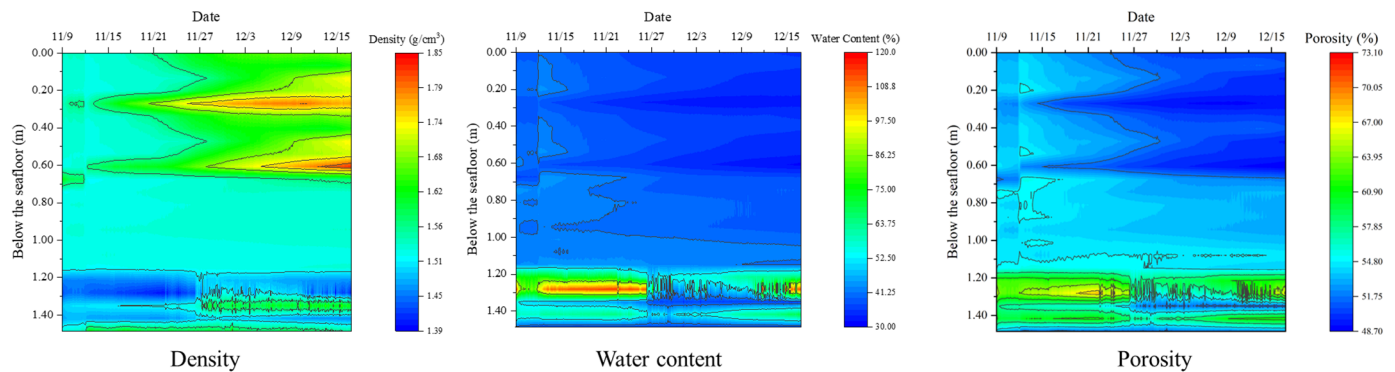


Figure 17. Variation in sediment density, water content, and porosity of Qingdao offshore sediment with time based on deep learning algorithm.

Sediment Density: The variation in seabed sediment density ranges from 1.39 to 1.85 g/cm³.

In the depth range of 0 to 0.7 m below the seabed, the density gradually increases over time. Significant increases in sediment density are observed at depths of 0.3 m and 0.6 m.

In the range of 0.7 to 1.15 m, the density shows minimal variation over time.

Between 1.15 and 1.51 m, the density slightly increases over time, but the values remain relatively low.

Water Content: The variation in water content ranges from 30% to 120%.

In the depth range of 0 to 1.2 m below the seabed, the water content decreases gradually over time.

Between 1.2 and 1.5 m, a significant peak in water content is observed, with a trend of first decreasing and then increasing as time progresses. This notable increase in water content suggests the presence of fluid migration pathways, such as water fractures, in this region.

Porosity: The variation in porosity ranges from 48% to 73%.

In the depth range of 0 to 0.7 m below the seabed, porosity gradually decreases over time.

Between 0.7 and 1.2 m, porosity slightly increases over time, though the change is smaller compared to the variation observed in the upper 0 to 0.7 m.

In the range of 1.2 to 1.5 m, porosity initially increases, then decreases, and increases again over time. The changes in porosity may be influenced by tidal variations in seawater.

5.3. Dynamic Changes in the Mechanical Properties of Subsea Sediments in the Qingdao Offshore Area

Based on the experimental data on the relationship between the velocity of sound in seabed sediments and their mechanical properties, we established empirical formulas that link sound velocity to parameters such as compressibility, shear strength, cohesion, and internal friction angle. With the results from the sound velocity measurements in the Qingdao offshore area, the spatiotemporal variation patterns of the mechanical properties of the seabed sediments were derived (Figure 18).

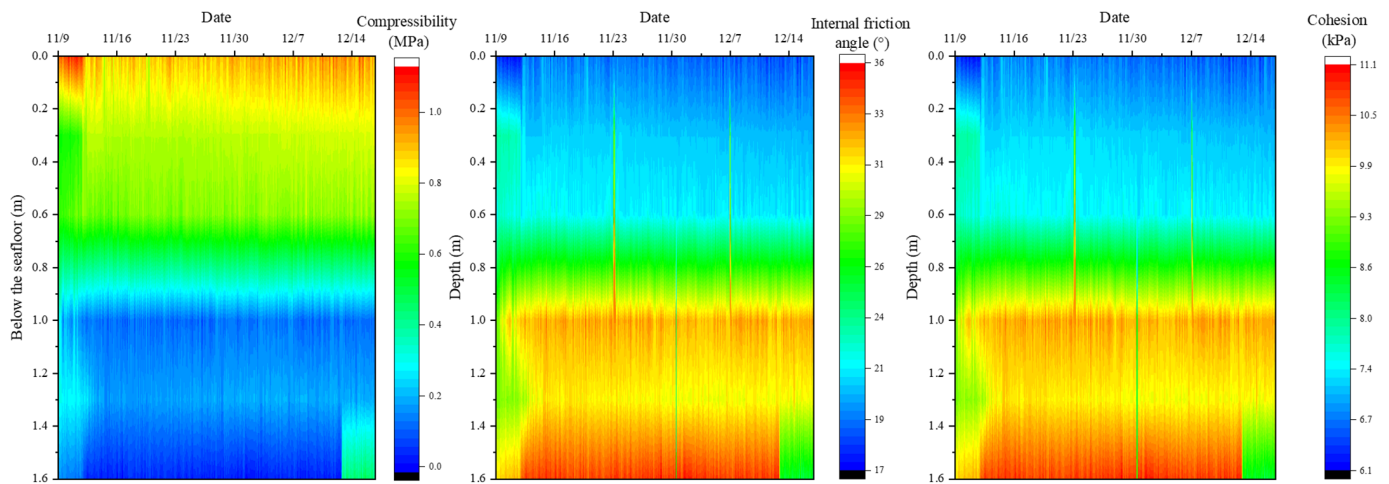


Figure 18. Time variation in compressive coefficient of seafloor sediment internal friction angle cohesion.

The range of compressibility in seabed sediments varies between 0.01 and 0.8 MPa. Vertically, the compressibility decreases with depth. Over time, the compressibility at different depths exhibits different trends. At a depth of 0.2 m below the seabed, the compressibility first increases rapidly, and then increases slowly. At 0.5 m in depth, the compressibility increases gradually over time. At depths of 0.9 m and 1.2 m, the compressibility increases rapidly at first, then stabilizes. At 1.5 m depth, the compressibility shows a trend of decrease, stabilization, increase, and stabilization. These dynamic changes in sediment compressibility reflect the evolving compressibility characteristics of the seabed sediments.

The range of cohesion in seabed sediments is between 7.05 and 11.13 kPa. Vertically, cohesion increases with depth, although it experiences an abnormal decrease at a depth of 1.2 m. Over time, at a depth of 0.2 m below the seabed, the cohesion first decreases sharply, then decreases slowly. At 0.5 m depth, cohesion decreases slowly over time. At depths of 0.9 m and 1.2 m, the cohesion initially increases rapidly, then stabilizes. At 1.5 m depth, the cohesion follows an increasing–stable–decreasing trend over time.

The internal friction angle of the seabed sediments varies between 20° and 36° . Vertically, the internal friction angle increases with depth but experiences an abnormal decrease at a depth of 1.2 m. Over time, at 0.2 m below the seabed, the internal friction angle decreases rapidly at first, and then decreases slowly. At 0.5 m in depth, the internal friction angle gradually decreases. At depths of 0.9 m and 1.2 m, the internal friction angle increases rapidly at first, and then remains constant. At 1.5 m in depth, the internal friction angle follows a pattern of increase, stabilization, decrease, and stabilization.

5.4. Analysis of the Dynamic Variation Process of Seabed Sediments in the Qingdao Offshore Area

During the observation period in the Qingdao offshore area, two significant wave events with wave heights greater than 1 m occurred. The first event took place from 11 November to 13 November, lasting 2 days, with a maximum wave height of 1 m. The second event occurred from 16 November to 20 November, lasting 4 days, with a maximum wave height of 2.2 m (Figure 19).

During the first wave event, from 11 November to 13 November, the maximum wave height was 1 m. During this period, the resistivity in the water slightly increased, as did the resistivity in the seabed boundary layer. The water resistivity showed a good linear relationship with the suspended sediment concentration [32], indicating that this wave event caused a significant increase in the concentration of suspended sediments. At a depth of 0.6 m below the seabed, resistivity decreased significantly, suggesting a reduction

in sediment density [33] and an increase in porosity [34]. In this layer, sediment sound velocity decreased markedly, approaching that of seawater, and the shear strength of the sediments also significantly dropped [35].

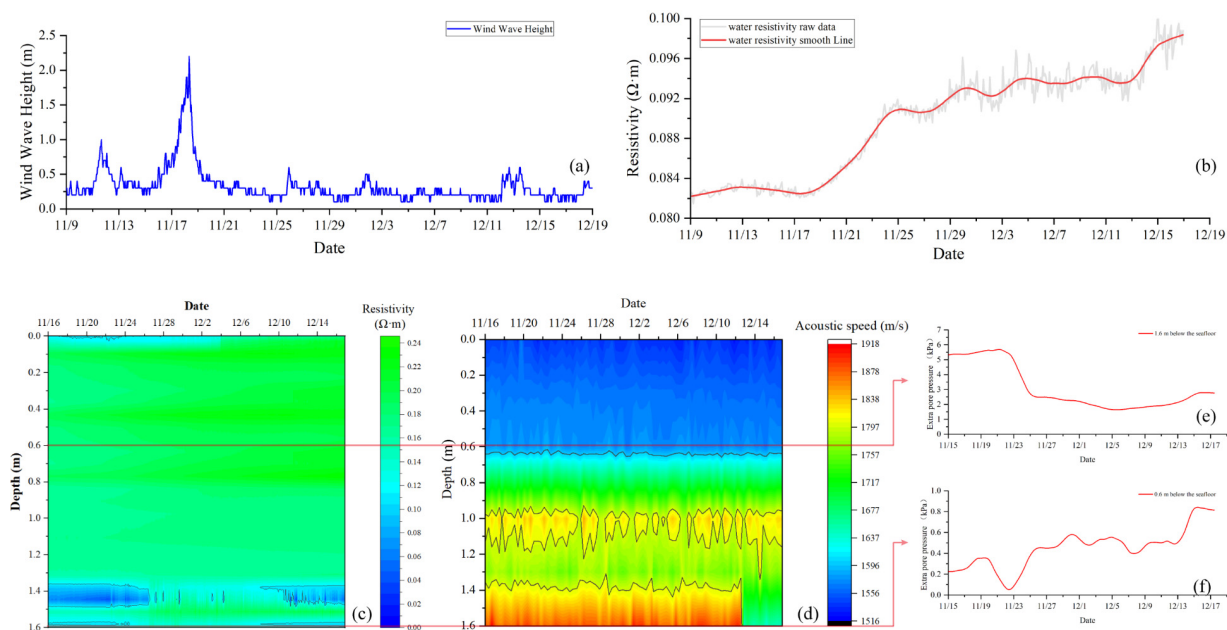


Figure 19. Dynamic change process of Qingdao offshore engineering geological environment: (a) high waves, data source: Wheat Island Observatory; (b) water resistivity; (c) sediment resistivity cloud; (d) sediment sound velocity cloud; (e) 0.6 m pore water pressure below the seabed; (f) 1.6 m pore water pressure below the seabed (the red arrows indicate the same depth). First Wave Event (11–13 November).

In the vertical structure, the resistivity of the overlying layer increased notably, indicating that this layer acted as an impermeable barrier [36], characterized by low porosity and high density [37]. Under wave pressure, pore water was mobilized upwards [38]. Due to the presence of this impermeable barrier, pore water accumulated in the layer, causing a sharp decrease in sediment resistivity [24]. At the same time, since the sound velocity in seawater was lower than that in sediment, the sound velocity in the sediment also decreased significantly.

At depths between 1.0 m and 1.8 m below the seabed (with pore pressure represented at 1.6 m depth), the resistivity increased significantly. The sediment porosity decreased, and the density increased [39]. The sediment sound velocity increased by 5%, compressibility decreased by 39%, cohesion increased by 7%, and the internal friction angle increased by 11% (Figure 20), resulting in a significant increase in shear strength [40]. In the vertical structure, the resistivity in this layer was low, approaching that of seawater, indicating that pore water was likely enriched in this layer. Under wave action, the excess pore water pressure decreased by 50%, releasing pore water from the sediment, which led to an increase in resistivity, a decrease in porosity, and an increase in density [41].

The second wave event occurred from 16 November to 20 November, with a maximum wave height of 2.2 m, peaking on 18 November. As the wave height gradually increased, water resistivity slightly decreased. This was likely due to the dilution of offshore seawater with low suspended particulate concentrations, which led to a decrease in water resistivity near the coast [42]. Concurrently, sediment deposition increased due to gravity, causing a slight increase in the resistivity of the seabed boundary layer.

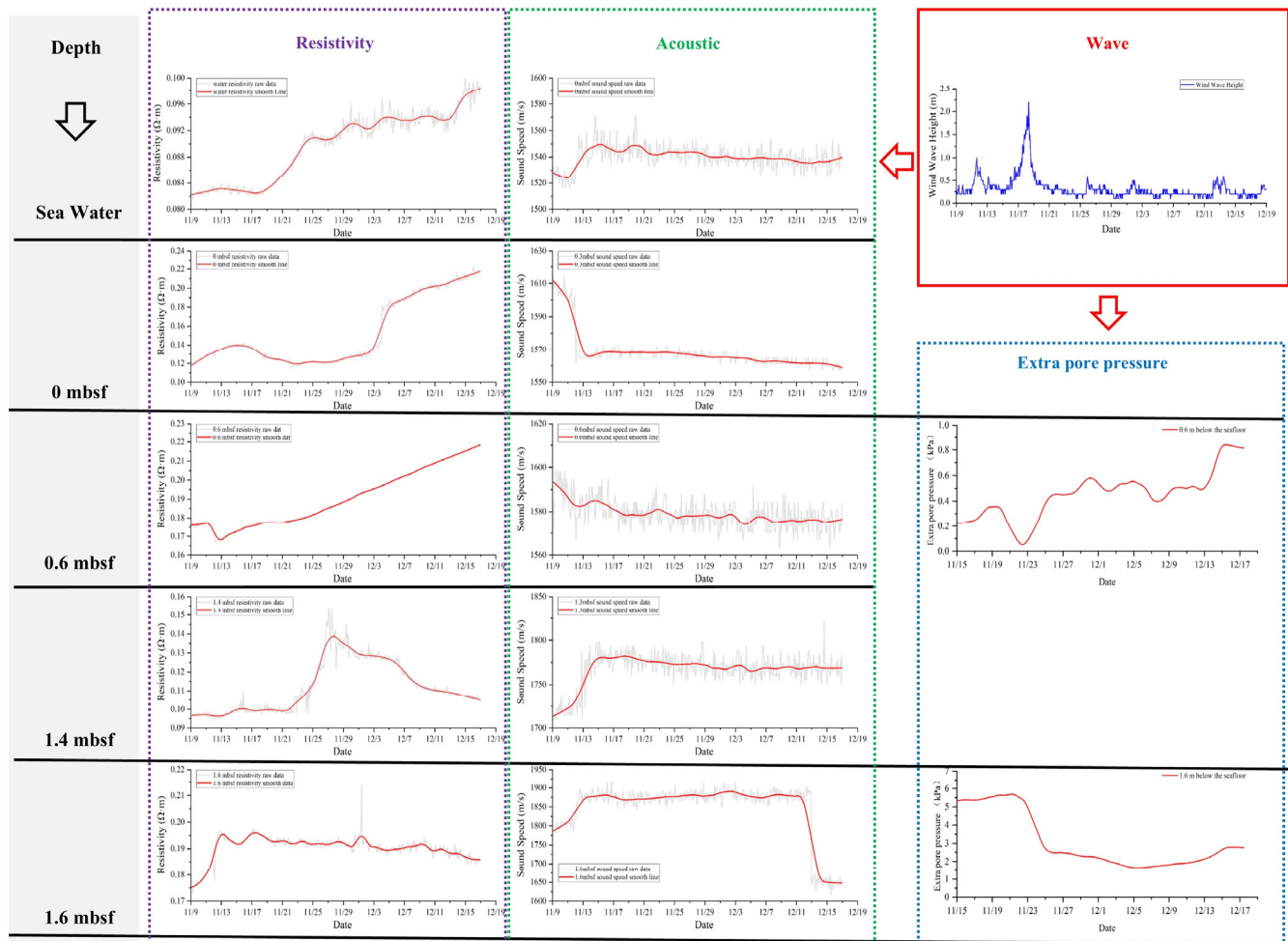


Figure 20. Dynamic changes in sediment resistivity, sound velocity, and excess pore water pressure at different depths in shallow seas. Second Wave Event (16–20 November).

Once the wave height began to decrease, significant changes in the sediment's engineering geological properties were observed [43]. From 18 November to 25 November, the water resistivity increased rapidly by 10%, indicating an increase in the concentration of suspended sediments. This increase was likely due to the resuspension of sediments from the seabed surface. Rijn [44] noted that under marine hydrodynamic forces, sediment particles undergo resuspension when the upward turbulent diffusion force balances the downward gravitational force.

From 16 November to 22 November, the resistivity of the seabed boundary layer continued to decrease, which confirmed the erosion of the seabed by the waves. From 22 November to 27 November, at a depth of 1.4 m below the seabed, sediment resistivity increased sharply. There are two possible reasons for this sharp increase.

In the vertical structure, the resistivity of this sediment layer was initially low, close to seawater resistivity, suggesting that this layer may have been enriched with pore water [29]. Under wave action, the pore water in this layer was likely released, leading to an increase in resistivity, a decrease in porosity, and an increase in density [45].

The wave action could have induced the vertical migration of pore water within the seabed sediments, which led to the upward migration of fine-grained sediments [46]. Due to the presence of an impermeable barrier in this layer, fine sediments accumulated, resulting in reduced porosity and increased compaction, which caused a rise in sediment resistivity. This finding closely matches the laboratory results of Jinguiji [33], who pointed out that permeability variations across different layers affect the dissipation of excess pore

water pressure. Low-permeability layers may act as barriers, preventing the vertical flow of pore water. In the presence of a fine-grained low-permeability layer within the seabed sediments, such layers can trap water from the underlying coarser sand, leading to lower resistivity and density.

5.5. Evolution Model of Pore Water Accumulation and Release in Seabed Sediments Under Wave Loading

As early as 1985, Clukey et al. [47] proposed that under wave cyclic loading, pore water pressure within sediments is prone to accumulation and dissipation, exhibiting unique dynamic response characteristics. Studies have shown that after storm events, liquefaction occurs in the surface layer of the seabed, forming a muddy layer up to one-quarter of the thickness of the liquefied layer [48]. Under extreme conditions, wave loading can induce liquefaction in shallow sediments within a depth range of 4.2 m beneath the seabed [49]. Zhang and Suhayda [50] found that under large wave conditions, the shear strength of the shallow seabed sediments can decrease by up to 77.7% within 24 h. Furthermore, in such conditions, the liquefaction of the shallow seabed sediments can lead to a significant increase in the concentration of suspended sediments in the underlying water [51]. The resuspension process of seabed sediments is largely dependent on the dynamic response to wave loading.

In 2016, Zhang et al. [52] pointed out that under wave cyclic loading, the strength of the seabed sediments rapidly decreases or even dissipates, leading to a sharp decline in shear strength and critical shear stress. Wen [20] studied the dynamic changes in the seabed boundary layer of the Yellow River Delta, proposing four evolutionary models: calm sea conditions, seabed consolidation with uniform vertical sediment concentration; small waves, acceleration of seabed consolidation with the boundary layer extending upward; medium waves, accumulation of excess pore water pressure in the seabed, and further upward extension of the boundary layer; and large waves, liquefaction of the seabed, with the boundary layer extending inward and increasing suspended sediment concentration in the water. This study also observed an increase in the background concentration of suspended sediments in the seabed boundary layer after a large wave event with a wave height of 2 m.

Building upon the above studies and the dynamic changes observed in the Qingdao offshore seabed, this study summarizes the dynamic evolution model of seabed sediment properties under wave loading in the Qingdao offshore area.

In the initial stage, under wave action, residual excess pore water pressure in the seabed gradually increases, causing pore water to accumulate beneath the impermeable layer. When the wave height decreases, the excess pore water pressure in the seabed becomes greater than that in the overlying sediments. At this point, pore water gradually moves upward, carrying fine particles from the sediments into the water, which increases the concentration of suspended sediments in the near-bottom seawater. As pore water is released from the sediments, excess pore water pressure decreases, and the volume of pore water gradually diminishes. When the excess pore water pressure beneath the seabed becomes smaller than that in the overlying sediments, pore water stops migrating upward, and fine sediment particles no longer move into the water, leading to a decrease in suspended sediment concentration in the near-bottom seawater. As wave action continues, residual excess pore water pressure in the seabed gradually increases again, returning to the initial stage, and the cycle repeats (Figure 21).

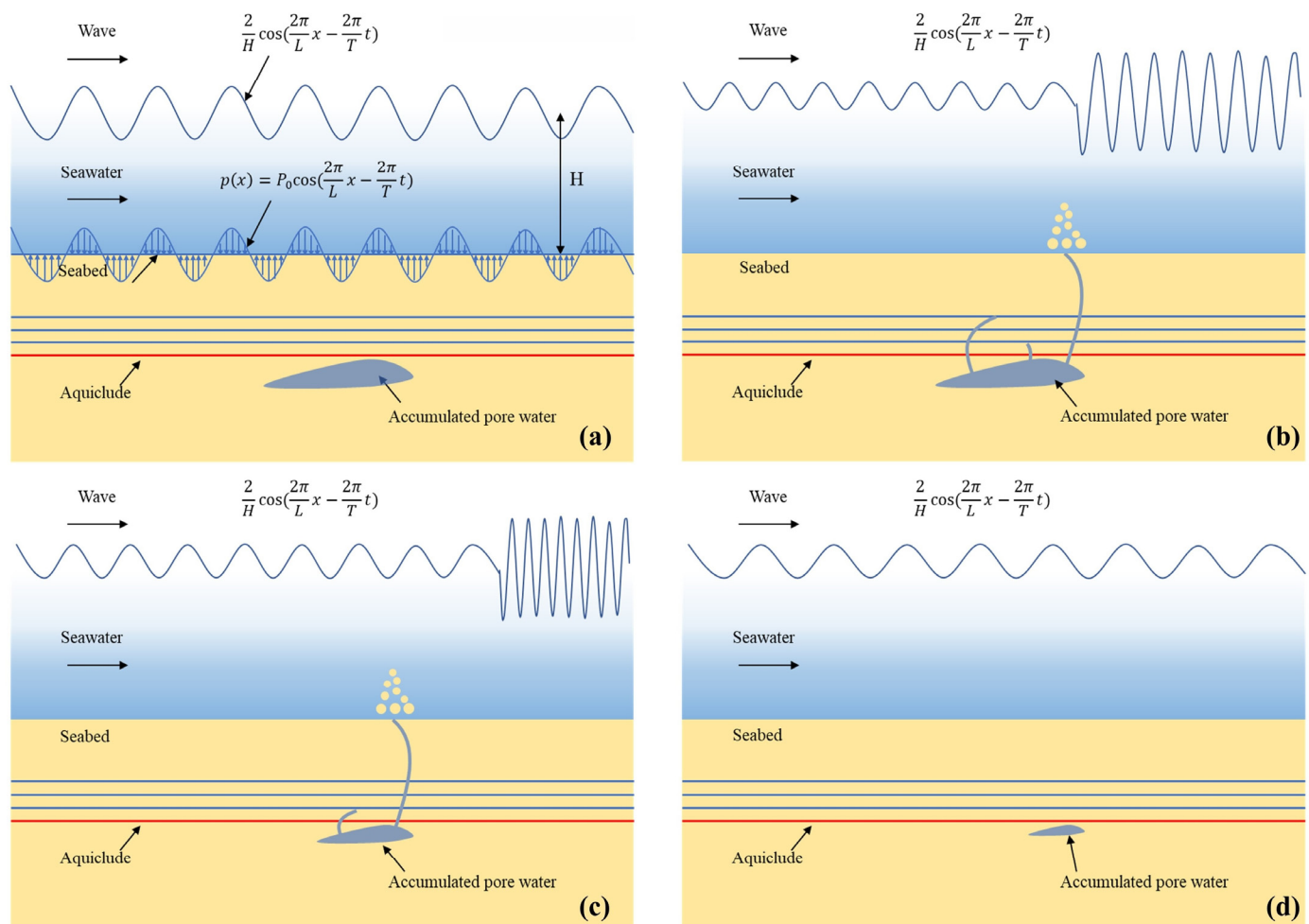


Figure 21. Dynamic variation patterns of pore water in sediments under different wave loads ((a) is the peak period of high waves when pore water accumulates [53]; (b) is the early stage of the recession period of high waves when pore water is released rapidly; (c) is the later stage of the recession period of high waves when pore water is released slowly; (d) is the calm period of waves when pore water accumulates partially).

Based on the observational data of acoustics, electrical resistivity, and pore pressure over one month, this study establishes a physical property model for electrical resistivity inversion and a mechanical property model for acoustic inversion. It reveals the dynamic changes in the engineering geological properties of offshore seabed sediments in the Qingdao offshore area under the action of wave loads and discovers the accumulation and release of seabed pore water caused by waves. The innovations in this paper are mainly reflected in two aspects. First, this study obtained in situ long-term observational data of the Qingdao offshore seabed for as long as one month, including acoustic data, electrical resistivity data, and pore water pressure data. Second, for the first time, it comprehensively analyzed the influence mechanism of wave loads on the cumulative release of seabed pore water and the changing process of the physical and mechanical properties of sediments by combining acoustics, electrical resistivity, and pore water pressure.

The limitations of this paper may be reflected in two aspects. First, since there were no wave and tide gauge in the observation equipment and the data from the nearby tide gauge station were adopted, there was a slight delay between the wave data and the real-time observation data. In the future, we will deploy integrated wave gauges for direct pressure gradient computation. Second, due to the multiplicity of solutions in electrical resistivity and acoustic inversions, the influencing factors are not unique. However, it is precisely

because acoustics and electrical resistivity can be continuously measured that it becomes possible to continuously monitor the dynamic changes in the physical and mechanical properties of seabed sediments, breaking through the singleness of traditional destructive measurement methods such as sampling measurements and cone penetration testing.

Based on the in situ monitoring of electrical resistivity, acoustics, and pore pressure, combined with the physical property model of sediment electrical resistivity inversion and the mechanical property model of sediment acoustic inversion, the continuous long-term monitoring of the physical and mechanical properties of seabed sediments can be achieved. Meanwhile, the physical properties, mechanical properties, and pore pressure of sediments can be used as inputs for the Biot consolidation model, providing the possibility for further rigorous theoretical analysis. This research has taken a step forward from previous studies on continuous single pore pressure measurements, realizing the dynamic long-term monitoring of the physical and mechanical properties of seabed sediments. This research provides new methods and new perspectives for comprehensively studying the dynamic changing process of the engineering geological properties of seabed sediments.

6. Conclusions

This study, based on an independently developed in situ monitoring system for sub-sea engineering geological environments, revealed the dynamic response mechanisms of sediment physical–mechanical properties under wave loading through a 36-day continuous observation in the offshore area of Qingdao. Key findings include the following: (1) Wave events with heights ≥ 1 m (maximum 2.2 m) triggered the cyclic accumulation and release of pore water pressure at 1.6 mbsf, leading to fluctuations in shear strength (cohesion increased 7%, internal friction angle increased 11%, and resistivity anomalies). (2) A deep learning model integrating multi-source data (resistivity, sound velocity, pore pressure) demonstrated significant spatiotemporal correlations between sediment density (1.39–1.85 g/cm³), porosity (48–73%), and a wave energy input within 0–1.5 mbsf. (3) An evolutionary model of “wave-induced pore water migration-rebalance” was proposed, elucidating the coupling mechanism of fine-particle resuspension (seawater resistivity increased 10%) and low-permeability layer blockage effects, which establishes a dynamic theoretical framework for assessing the long-term stability of subsea pipelines and foundations in monsoon-dominated coastal regions.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

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