Monitoring and Early Warning Technology of Hydrate-induced Submarine Disasters

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Abstract. With the depletion of fossil energy sources, such as coal and petroleum, natural gas hydrate has been proposed as an alternative energy source. However, the synthesis of natural gas hydrate may cause marine engineering disasters, such as submarine cable breaks and the collapse of sub-sea oil rigs, and even submarine earthquakes, triggering tsunamis and seriously endangering human safety. Hydrate test production monitoring in various countries focuses on the temperature, pressure, and methane concentration near test production wells. Effective observation equipment and methods for the monitoring and early warning of submarine geological hazards are lacking. This paper reviewed the possible geological hazards caused by deep seawater hydrate mining and the monitoring and early warning technologies for deep seawater hydrate mining in various countries and introduced the in-situ Surveying Equipment of Engineering Geology in Complex Deep Sea (SEEGeo). The equipment uses 3D resistivity measurement and data inversion technology, seabed sediment acoustic measurement and data inversion technology, seabed sediment pore water pressure measurement and data inversion technology, and renewable energy seawater-dissolved oxygen battery power supply technology. SEEGeo can realize the in situ, real-time, long-term, effective monitoring and early warning of geological disasters induced by hydrate development. At present, the equipment has conducted two sea trial experiments on the continental slope of the South China Sea, equipped with the “Marine Geology No. 6” scientific research vessel of the Guangzhou Marine Geological Survey and the “Dongfanghong No.3” scientific research vessel of the Ocean University of China, and obtained in situ engineering geological data of the South China Sea.

1. Introduction

As a new type of unconventional energy, natural gas hydrate has the advantages of wide distribution, abundant reserves, and high combustion efficiency [1]. Natural gas hydrates are widely distributed in the world; most of them are distributed in the sediments of the deep-sea continental shelf, and a few are distributed in the polar frozen soil. According to statistics, the carbon content of natural gas hydrates is twice that of fossil fuels on earth [2]. Therefore, many countries plan to carry out hydrate mining to make up for the energy shortage and optimize the energy structure. Among them, Japan, the United States, and China have already conducted trial production of natural gas hydrates. Natural gas hydrates have many advantages, and the exploitation may induce a series of serious natural disasters, including aggravating the greenhouse effect, destroying the seabed ecosystem [3], and inducing seabed geological hazards [4]. Among them, geological hazards, such as submarine landslides and subsidence,
may cause submarine cable breaks and trigger the collapse of submarine oil rigs and other marine engineering disasters [5]. The geological hazards induced by hydrate decomposition may even induce seafloor earthquakes, trigger tsunamis, and seriously endanger human safety [6]. Therefore, this issue warrants investigation.

The geological geohazards induced by deep-sea hydrate exploitation may pose a threat to the safety of marine engineering and coastal personnel. Thus, the research on the monitoring and early warning technology of submarine geological hazards induced by natural gas hydrate exploitation must be strengthened. Given that the trial production of natural gas hydrates has started in various countries, the research on this issue is important and imminent.

At present, all countries have carried out relevant studies and monitoring experiments on geological hazards induced by deep-sea natural gas hydrate production. Among them, in 2013 and 2017, Japan carried out two trial productions of deep-sea natural gas hydrates successively. Japan also conducted monitoring projects, such as temperature and pressure monitoring, seafloor deformation monitoring, and submarine methane leakage monitoring [7–10]. In 2012, the United States conducted a trial production of natural gas hydrates in Iginik Sikumi on the northern slope of Alaska. The trial production was conducted using gas replacement. The actual trial production time was one month, and the gas production was about 28,300 m³ [11]. In 2002, the Canadian Geological Survey (GSC) conducted trial production in the Mackenzie Delta of the Beaufort Sea in North America. During the trial production, two monitoring wells were drilled, and distributed fiber temperature sensors were used to monitor the temperature change of the hydrate reservoir [12,13]. In 2017 and 2019, China conducted two trial production of the subsea natural gas hydrate in the South China Sea and established the “four in one” environmental monitoring system for the atmosphere, seawater layer, seafloor, and below the seafloor [14].

The aims of trial production monitoring were to study the decomposition of hydrate reservoirs and the impact of methane gas release on the ecological environment, the monitoring of hydrate mining focused on temperature, pressure and methane concentration. Accordingly, few studies monitored the geological hazards induced by hydrate mining.

In response to this problem, this paper briefly summarizes the hydrate-induced geological disasters and the monitoring technologies of seabed natural gas hydrates in various countries and introduced the monitoring and early warning system of the geological hazards induced by deep-sea natural gas hydrate exploitation, which was developed by our team, to offer help for the safe exploitation of submarine gas hydrates.

2. Hydrate decomposition-induced geological disasters

Although natural gas hydrates have many advantages, their synthesis causes many environmental problems, such as aggravating the greenhouse effect, destroying the seabed ecology, and inducing geological disasters. The following focuses on the introduction of hydrate-induced geological disasters. At present, geological disasters are divided into two categories: natural geological disasters caused entirely by natural geological processes and industrial geological disasters caused by human activities [15].

2.1. Natural geological disasters

Natural geological disasters have many types, including seismic activity, shallow water flow, shallow gas accumulation, submarine landslides, pockmarks, and mud volcanoes, as shown in Figure 1 [16]. Natural geological disasters related to hydrate decomposition include submarine landslides, pockmarks, and so on.
Figure 1. Various geological hazards that may occur on the continental slope [16].

Natural gas hydrates induce submarine geological disasters through the following mechanism. Before hydrate formation, large amounts of methane gas and water move freely in the pores of the sediment. During hydrate formation, methane gas and water become a solid hydrate. The solid hydrate, confined in the pores of the sediments, is relatively stable and becomes part of the sediments. It also hinders the normal consolidation and mineralization process. As the amount of natural gas hydrates increases, the permeability of sediments gradually decreases. Eventually, the natural gas hydrate becomes part of the sediment. As the deposition process continues, the sedimentation process causes the natural gas hydrate to be buried deep underground, the pressure increases, and the temperature increases. When the temperature of the hydrate stabilization zone bottom exceeds the decomposition temperature of the hydrate, the natural gas hydrate at the bottom becomes unstable. At this time, the hydrate decomposes (1 m³ hydrate decomposition produces 164 m³ gas and 0.8 m³ water). The sediment cemented by gas hydrate becomes a solid–liquid–gas mixture. In addition, a large amount of gas generated by the hydrate decomposition generates excess pore pressure. The solid–liquid gas layer generated at the bottom of the hydrate zone may cause submarine slope destruction under the action of gravity [17].

Submarine landslide
Submarine landslide is an important marine geological disaster widely distributed around the world, and many of them are related to the natural gas hydrate.
Figure 2. Global submarine landslides distribution related to the decomposition of natural gas hydrates (modified from [18]).

Hydrate-induced submarine landslides in the world include the following: Norway’s Storrega landslide is the largest submarine landslide induced by natural gas hydrate decomposition. The Storrega landslide experienced three landslides; the second landslide was caused by natural gas hydrates at least [19–22]. The Cape Fear landslide on the US Atlantic continental slope of the US Atlantic was also caused by hydrate decomposition. Paull et al. believed that the sediment samples of this landslide body lack the sediment sequence of 14–25 ka, which might be due to the hydrate decomposition caused by the sea level drop during the last glacial period, causing submarine landslides [23]. The landslide of the Amazonian alluvial fan in South America was also caused by hydrate decomposition. Two landslides formed during the rapid decline of sea level at 35 and 42–45 ka. The decomposition of natural gas hydrates caused by the decline of sea level possibly triggered the landslide [24].

The landslides of the Beaufort on the northwestern coast of Canada, the Balearic deep-sea plain in the western Mediterranean, the continental shelf of West Africa, the continental shelf of Colombia, the Pacific coast of the United States are closely related to the decomposition of natural gas hydrate [24–28].

Large-scale submarine landslides not only destroy deep-sea oil and gas drilling, oil pipelines, submarine cables, and subsea engineering facilities but also cause tsunamis, which greatly endanger the safety of people’s lives and properties. This understanding is important to the exploration of natural gas hydrate and the construction of subsea engineering facilities.

Pockmarks
Pockmarks refer to the collapse pockmarks of different shapes, sizes, and scales formed by the continuous overpressure fluid, which is under the seabed. The formation of pockmarks landform is closely related to the seabed methane leakage and active fluid migration. Seabed pockmarks were first discovered in the 1970s. King [29] discovered a crater-like depression in the Nova Scotia continental shelf in Canada, but it was not valued by people. Until 1987, Hovland [30] found authigenic carbonate cement in the sag terrain when studying the topographic sediments of the submarine sag in the North Sea and linked submarine pockmarks to methane leakage activities. Pockmarks could indicate the fluid activity on the seabed and connect with methane hydrate. Currently, seafloor pockmarks are found in many seas around the world, such as the West African Sea [31], the
Northern Norway Sea [32], the Bering Sea [33], the western Canada Sea [34], the Gulf of Mexico [35], the Black Sea [36], and the South China Sea [37].

Pockmarks indicate the existence of submarine oil and gas reservoirs and gas hydrate. In pockmark formation, different types of fluid may produce different types of pockmarks. For the formation mechanism of pockmarks, Kelley proposed two mechanisms of formation. The first is the equilibrium mode, in which fluid leaks through thousands of years to form pockmarks; the second is the catastrophic mode, in which factors such as earthquakes, tsunamis, and storms reduce the pressure of the upper layer of the gas reservoir. The fluid suddenly leaks or erupts, and a large amount of muddy sediment is transported to form a pockmark [37].

As an indicator of subsea fluid leakage, pockmarks provide important information for monitoring the stability of submarine landslides, such as how the abnormal pressure on the seabed is formed and circulated. In addition, the activities of submarine pockmarks may cause potential safety hazards in submarine projects.

2.2. Industrial geological disasters

The industrial geological disasters related to natural gas hydrates are caused by oil and gas production activities. These disasters occur in deep seawater hydrate mining and permafrost area hydrate mining. Such disasters can be divided into the following four categories:

- Stability problems of the artificial infrastructure.
- Drilling risks when hydrate reservoirs are encountered during drilling.
- Methane gas with higher temperature in the deep hydrate reservoirs re-condenses when it moves to the shallow layer and becomes cold, blocking the oil pipeline.
- Reservoir destruction caused by production from hydrate reservoirs.

![Figure 3. Natural and industrial geological disasters related to natural gas hydrate [15].](image-url)
3. Submarine natural gas hydrate monitoring technology
Deep-sea natural gas hydrate monitoring is used for the comprehensive monitoring of environmental changes caused by hydrate. Monitoring technology is classified by space, including monitoring of the atmospheric environment above the sea surface, monitoring of the marine water environment, and monitoring of the seabed environment. At present, many countries have carried out monitoring of deep-sea hydrate. Among them, some countries have even conducted trial production of submarine natural gas hydrate. The following sections discuss the hydrate monitoring technology in Japan, the United States, South Korea, Europe, and China.

3.1. Monitoring of the first trial production of natural gas hydrate in Japan
In 2013, Japan successfully carried out the first offshore trial production of natural gas hydrate in Japan. It was also the world’s first offshore gas hydrate production. The monitoring technologies used in the hydrate exploitation in Japan include well monitoring, seabed monitoring, and submarine boundary layer monitoring.

![Figure 4](image-url) Schematic of production and monitoring wells in Japan in 2013 [38].

**Well monitoring**
The project drilled a production well and two monitoring wells. The monitoring well is mainly used for temperature monitoring, including distributed temperature sensing (DTS) and resistance temperature detector (RTD) sensors, specially designed for subsea batteries with programmable measurement schedules, through connection and sound wave communication. Among them, the DTS sensor is placed at intervals of 0.5 m, covering the entire drilling hole with an accuracy of 0.5 °C. The RTD sensor is placed at intervals of 2 m, only covering the hydrate reservoir with an accuracy of 0.1 °C. The temperature monitoring in the monitoring well had started one year before natural gas hydrate production and lasted half a year after production to monitor the long-term stability of natural gas hydrate reservoirs [39].

![Figure 5](image-url) Configuration of the in situ temperature monitoring system in the monitoring well [39].
Seabed monitoring
The seabed monitoring system includes a seabed deformation monitoring system, a four-component seismic monitoring system, and a methane monitoring sensor [7]. The seabed deformation monitoring system includes floating body materials, beacons, and flashlights for identifying positions, counterweights, acoustic releasers, batteries, data recorders, and four other sensors. The four sensors of the system are a pressure sensor, an inclinometer, a magnetic compass, and a thermometer to measure the subsidence deformation and inclination of the seabed. The pressure sensor calculates the vertical deformation of the seabed by measuring the changes in the seabed depth, the inclinometer is used to measure the 3D inclination of the seabed, the magnetic compass is used to measure the azimuth of the sensor, and the thermometer is used to measure the temperature of the seawater. The pressure sensor is equipped with a quartz crystal resonator with a measurement range of 0–14 MPa (0–1400 m), a resolution of 0.14 Pa (0.014 mm), and an accuracy of 0.1 kPa (10 mm). The inclinometer is equipped with a liquid electrolyte for measurement at the range of ±30°, a resolution of 0.001°, and an accuracy of 0.02° [40]. The pressure sensors are placed at the seabed around the production well and at the reference point, which is 100 m away from the production well, to obtain the pressure difference between the two places before and after the hydrate trial production. The monitoring started 2 months before the hydrate trial production and continued for another 2 months after the trial production to determine the long-term subsidence of the seabed.

Figure 6. Schematic of the seabed deformation monitoring system and monitoring plan [40].

Japan also uses the deep-sea seismic four-component monitoring system to monitor methane hydrate production experiments. The system includes geophones and receivers of the electro-optical telemetry circuit. The receiver uses the submarine optical cable serial connection for real-time data collection and recording. The original receiver is modified by reducing the volume of the accelerometer and hydrophone to 2/3, making it more compact, lighter, and easier to deploy to the deep sea than before. The receiver shell has a metal protective outer box. The submarine optical cable is protected by a steel shield armor, which could be deployed by the ROV at the water depth of 2000 m. The device monitors the long-term reflection seismic to study the changes before and after hydrate production [41,42].
Submarine boundary layer monitoring
Submarine boundary layer monitoring consists of the methane leak monitoring system (MLMS). The MLMS includes a methane sensor (METS), a temperature sensor, a salinity sensor, and an ammeter [43].

3.2. Second trial production monitoring of natural gas hydrate in Japan in 2017
Following the first trial production of natural gas hydrate in Daini-Atsumi in 2013, Japan began the second trial production of natural gas hydrate from April to June 2017, which was 75 m away from the trial production site in 2013 with the water depth of 1000 m (K. Yamamoto et al., 2019).

Japan had obtained the environment data, such as 3D seismic exploration and resistivity logs, before the two trial productions. Two production wells and two monitoring wells were drilled in this trial production. The first test well (AT1-P3) lasted 12 days, and the second test well (AT1-P2) lasted 24 days. The monitoring device in the production includes seven real-time temperature and pressure sensor arrays and two self-recorded temperature and pressure sensor arrays. In the monitoring wells, two types of temperature sensors (optical fiber DTS and electronic RTD) are used to record the temperature changes during the trial production. Two pressure sensors are also installed in each monitoring well. The pressure and temperature sensors in the monitoring well (AT1-MT2/MT3) could continuously collect data for 2 years to measure the changes in the hydrate reservoir before and after the trial production due to the long-term methane hydrate decomposition near the test well. In addition, the measurement equipment installed in the monitoring well also includes seabed data storage, rechargeable batteries, acoustic communication system, and so on [10].
Since the pressure sensor array, which was distributed along with the temperature sensor array, was added to the monitoring well during the second hydrate trial production in 2017, the fluid density can be obtained by calculating the difference in the fluid flowing through the two adjacent pressure sensors and the temperature information, reducing the uncertainty of gas and fluid flux calculation results [10].

3.3. United States

The United States hydrate trial production was exploited onshore in Alaska. Although the United States seabed natural gas hydrate was not formally exploited, the corresponding monitoring and research works started in 2002. The hydrate-rich area in the Gulf of Mexico was selected as the observation area.

The Gulf of Mexico Hydrate Research Consortium established a monitoring station/seafloor observatory in the MC118 block of the Mississippi Canyon in the northern Gulf of Mexico at a depth of 900 m for the long-term monitoring (estimated 10 years) of the submarine natural gas hydrate in the Gulf of Mexico. The monitoring station consists of a seismic acoustic receiver array located on the seabed and a biochemical monitoring array located in the seawater for observing microbial activity (McGee et al., 2008).

Before monitoring, the surface morphology of hydrate mounds was investigated through high-resolution seismic, multibeam sonar, underwater cameras. The structural profiles of submarine sediments were obtained through the side-scan sonar and 3D seismic techniques on an autonomous underwater vehicle (AUV). In addition, the sediment was collected to study the lithology and biogeochemical characteristics of near-surface sediments [44].
During monitoring, the seabed observation station consisted of the following sensor arrays. The pore fluid array is used to collect samples and analyze the chemical characteristics of pore fluids [45].

The vertical line array (VLA) and the horizontal line array (HLA) are used to detect the geological structure and material composition of the seabed. The VLA and the HLA could use the noise generated by the ship as an active sound source and the environmental background noise as a passive seismic sound source. In addition, the accelerometers are added to the HLA to monitor earthquakes on the seabed passively. The chimney sampler array is placed in the bacterial community area and the bubble area to measure the gas flux overflowing from the seabed.
The fiber optic cable is armored with a total length of 4000 m. It is used to connect surface ships and submarine instruments. An AUV is used to obtain the topographic map of the seabed and collect images of Woolsey hills. A multibeam sonar rotator (MSR) is used to quantitatively analyze the overflow flux of methane gas. MSR adopts the vertical scanning mode, which could scan and obtain 3D water information with a radius of up to 50 m, with a rotation rate of 10°/s. The scanning sonar is connected to the sea surface through a cable to adjust the sonar parameters (such as scanning range, gain, and measurement frequency).

The rotating camera system could continuously visualize and observe suspended matter in the seawater. The equipped infrared camera could also record the changes in seabed temperature. The benthic boundary layer array includes methane sensors to monitor the gas escaping from the seabed to the seawater. As the subsea relay station, the integrated data power unit is used to connect various instruments and collect data from the instruments [47,48].
3.4. South Korea
The Korea Institute of Geoscience and Mineral Resources planned to develop a subsea environmental monitoring system for the trial production of natural gas hydrate in the northern Ulleung Basin of South Korea. The goal of the seabed monitoring system is to monitor the environmental changes in the seawater and the seabed changes caused by methane leakage due to drilling activities or trial production [49].

The seabed monitoring system plans to use pressure sensors and inclinometers on the seabed to observe the deformation of the seabed; pressure sensors and distributed temperature sensors are installed along the borehole to observe hydrate decomposition. The seabed undergoes vertical and inclined deformation. The seabed vertical deformation plans to use the high-precision pressure sensor of the Paroscientific Digiquartz series to measure the changes in water depth pressure. The resolution of the precision pressure is 10 ppb, indicating that water depth pressure changes of 1 µm could be distinguished in a water depth of 100 m. The inclinometer has been widely used for the seabed tilt measurement in marine geophysical surveys, with an accuracy of 0.002° [49].

![Figure 16. TPplanned monitoring system for the Ulleung Basin in the East China Sea [49].](image)

3.5. European Seabed Observation Network (ESONET)
The ESONET aims to establish a multidisciplinary marine long-term observatory located in the European deep-water area and selected 11 sea areas, such as the Atlantic Ocean and the Mediterranean Sea, as the regional observatory. The ESONET includes more than 50 institutions and enterprises in 14 countries in Europe, with a total of about 300 scientists, engineers, and technicians.

In 2001, scientists from Norway, France, and Germany proposed to establish two hydrate-related observatories on the Norwegian border, which is near the largest Storegga landslide (one known to be the largest submarine landslide induced by the hydrate decomposition), and the Black Sea [50].

Observation equipment includes a subsea seismograph (OBS), temperature sensors, and chemical sensors (for pH, O₂, sulfide, and redox).
When studying the activity of the warming bottom seawater and seism, the Black Sea node found that the pressure and temperature changes in the hydrate monitoring area caused the decomposition of natural gas hydrate and the release of methane.

3.6. China
From May 10th to July 9th, 2017, the China Geological Survey conducted the first seafloor hydrate production test in the Shenhu area of the South China Sea. It produced gas continuously for 60 days with total gas production of $3.09 \times 10^5$ m$^3$. The main sediment type in the production area is clay silt fine-grained sediment with a water depth of 800–1600 m and an average slope of 4.5° [51].

Before the trial production, China conducted 13 marine environmental surveys near the trial production area and obtained the background concentration values of methane and carbon dioxide in the atmosphere and seawater, in the biological environment of the ocean, and in the geological environment of the seafloor. The “four in one” environmental monitoring system was used to monitor methane leakage and changes in the marine environment that might be caused during the production process; after the trial mining, the comprehensive marine environment survey was conducted to determine the impact of hydrate trial mining on the entire marine environment [51].

In hydrate trial production, a “four in one” environmental monitoring system including the atmosphere, seawater, seabed, and below the seabed was established. The atmospheric monitoring system includes...
A sea–air interface flux monitoring system to identify methane gas leaking into the atmosphere from the seawater. The seawater monitoring system includes ROV, CTD, and METS monitoring system, the submarine monitoring system. The improved METS system has the measurement range of 10–500 nmol/L and a resolution of 1 nmol/L. It can be mounted on CTD, submersible, and ROV to monitor the leakage of methane at the seawater. The submarine monitoring system is placed at 87 m southwest of the trial well. The sampling frequency of the methane sensor was 12 h 40 min, and the sampling time was 5 s. The subsea monitoring system includes a subsea buoy detection system to monitor methane leakage and environment change of the seabed. The monitoring below the seabed includes four monitoring wells to monitor the temperature and pressure changes of natural gas hydrate. Two heat flow meters were installed in the monitoring wells at 1530 m and 1307 m, respectively. An optical fiber temperature observation system was also installed in the monitoring well [52].

**Figure 19.** “Four in one” environmental monitoring system during the trial production of natural gas hydrate [52].

The overall development trend of the seabed monitoring and warning technology in the world is the “four in one” environmental monitoring system, including the atmosphere, seawater, seabed, and below the seabed. The monitoring systems mainly focus on the atmosphere, seawater monitoring, and the monitoring of temperature, pressure, and methane concentration. However, the geological hazards induced by hydrate mining were rarely monitored, which will be the trend of the seabed monitoring and warning technology.

### 4. Monitoring and early warning system for geological disasters induced by deep-sea natural gas hydrate trial production

In situ Surveying Equipment of Engineering Geology in Complex Deep Sea (SEEGeo) has been developed for the monitoring and early warning of geological disasters induced by deep-sea natural gas hydrate production. SEEGeo can achieve 12 months of continuous in situ observation at the maximum water depth of 1500 m. The equipment can carry out the stereoscopic observations of the engineering parameters of seafloor sediments, the accumulation of excess pore water pressure, the process of seafloor topography erosion and deposition, and seawater dynamic conditions. The observation data can be transmitted to the remote server in real time. It can also be stored on the seabed observation device.
The submarine sediment engineering property parameters can be obtained by 3D electrical measurement and acoustic measurement of the seabed. Sediment index parameters, such as sediment particle size, bulk density, water content, and porosity ratio, can be obtained through the in situ long-term observation of the spatio-temporal changes of seabed sediment resistivity, sound speed, sound attenuation, and geophysical inversion analysis. Combined with laboratory mechanics testing, the relationship between the seabed resistivity, acoustic parameters, and soil deformation and strength indicators can be established to quantitatively describe the dynamic changes of hydrate-induced seafloor geological disasters.

The accumulation of sediment excess pore water pressure and the changes of seafloor topography can be obtained by the real-time measurement of the pore water pressure probe and the resistivity probe penetrating the seabed sediment. The excess pore water pressure is directly measured by a differential pressure sensor; the change of the sea bed position is determined by the resistivity value of the seawater and sediment measured by the resistivity probe, according to the sudden change of the resistivity value at the interface between the sediment and seawater.

The seawater dynamic conditions, such as the flow rate, flow direction, and sand content of the bottom seawater, can be measured by the current meters and turbidimeters in real-time.

Currently, the long-term power supply of seafloor observation instruments is a worldwide technical problem. Our team has developed a seawater dissolved oxygen battery that uses the electrochemical reaction between magnesium and dissolved oxygen in seawater electrolyte to generate electrical energy, achieving low-cost, environmental protection, and sustainable power supply for long-term observation instruments on the seabed.

The seabed observation equipment, seawater battery, and counterweight are installed on the carrying platform and placed on the long-term observation point.

The seabed observation data collected on the spot can be transmitted to the buoy located on the sea surface using underwater acoustic communication and then transmitted to the computer server via satellite remotely for client access.

### 4.1. Overall structure

The overall structure of SEEGeo consists of three parts: the observation instrument located on the seabed and its carrying platform, the data transmission buoy located on the sea surface, and the remote data management servers.

![SEEGeo overall structure diagram](image)

**Figure 20.** SEEGeo overall structure diagram.
The seafloor observation instruments of SEEGeo include a seabed sediment resistivity 3D measurement sensor and an acquisition controller; a pore water pressure measurement probe and acquisition controller; a seafloor sediment acoustic measurement probe and acquisition controller; and seawater flow velocity and turbidity measurement devices.

The SEEGeo platform is also equipped with a hydroacoustic communication device that can communicate with the sea surface buoy, a seawater battery that provides electricity for observation, a tilting measurement sensor, and a seabed ranging sensor for monitoring the deployment of instruments.

![Figure 21. SEEGeo system composition.](image1)

The data transmission buoy of SEEGeo located on the sea surface is equipped with underwater acoustic communicators, satellite communicators, and solar power supply devices. It can automatically and bidirectionally communicate with seabed observation instruments and BeiDou satellites in real-time for the long-term observation data and observation instructions.

![Figure 22. SEEGeo system composition.](image2)

The equipment includes four probes, each of which is 3 m. The sensors of the probes are distributed. The pore pressure includes four fiber grating differential pressure sensors with a pitch of 1 m. The resistivity probe includes 60 electrode rings with a pitch of 65 mm. The two acoustic probes include one transmission transducer and three high sensitivity acoustic transducers.
Figure 23. SEEGeo system composition.

### Table 1. Main technical parameters of the equipment

| Indicator                        | Parameter       |
|----------------------------------|-----------------|
| Equipment underwater weight      | 2 t             |
| Equipment weight                 | 2.5 t           |
| Penetration force                | 1.5 t           |
| Probe penetration depth          | 3 m             |
| Number of probes                 | 4               |
| Dimensions                       | 2 m × 1.8 m × 2.2 m |
| Working depth                    | 3000 m          |
| Placement method                 | Geological winch|
| Type of observation              | Acoustics, electricity, excess pore pressure |

4.2 Sea trial experiments on the continental slope of the South China Sea

At present, the equipment has conducted two sea trial experiments on the continental slope of the South China Sea, equipped with the “Marine Geology No. 6” scientific research vessel of the Guangzhou Marine Geological Survey and the “Dongfanghong No. 3” scientific research vessel of Ocean University of China, and obtained in situ engineering geological data of the South China Sea.

In May 2019, the observation equipment was equipped with “Marine Geology No. 6,” and a deep-sea trial was carried out on the northern slope of the South China Sea (water depth: 1450 m). The data and working status of each sensor were obtained when the equipment was located at water depths of 500, 1000, and 1400 m.

In June 2019, the observation equipment was equipped with “Dongfanghong No. 3,” and a deep-sea trial was carried out on the northern slope of the South China Sea (water depth: 1560 m). The equipment was penetrated, and the acoustics, resistivity, and pore pressure of the seabed sediments were obtained. Settlement deformation of the seabed and environmental factors, such as temperature, salt, depth, flow, turbidity, dissolved oxygen, and methane concentration, were also determined.
Figure 24. First sea trial in the South China Sea.

Figure 25. Second sea trial in the South China Sea.

Equipment deployment of SEEGeo:
1) Near the sea trial area, unfix the equipment in advance, hang the equipment with safety ropes, and hoist the equipment to the rear deck work area with a folding arm. Hang the geological cable and install four wooden supports. Install the four probes of resistivity, pore pressure, and acoustics in sequence, and manually obtain the sensor data of resistivity, pore pressure, and acoustics to confirm that each collection warehouse is working properly; 2) Start the dynamic positioning of the ship, use the A frame to hoist, place the equipment into the water and hover for 5–10 min, carry out the sound communication test, and obtain the instrument parameters; 3) Lower the equipment at a uniform speed of 0.5 m/s (the lowering speed of the equipment can be adjusted at any time according to the situation to ensure that the geological cable is in a stressed state). When the equipment descends to depths of 200, 500, 800, 1000, and 1200 m, collect the sensor data of each probe; 4) After sitting on the bottom steadily, obtain the device attitude data and penetrate the four probes in sequence. Obtain azimuth attitude and displacement data. Collect posture, lithium battery voltage, resistivity, pore pressure, and acoustic data; 5) Set the automatic continuous acquisition parameters, enter the automatic working mode, and monitor the working status of each sensor through sound communication; 6) After the automatic collection test is completed, pull out the probe, recover the equipment, and disassemble the probe.

5. Summary and Outlook
Seabed natural gas hydrate has attracted much attention. Japan and China have succeeded in the trial production of the seabed natural gas hydrate. The United States, South Korea, Europe, and India have conducted many researches and prepared for the trial production of seabed natural gas hydrate. The in situ long-term monitoring of the seabed environment induced by the trial production of natural gas hydrate needs to be strengthened.

At present, the monitoring technologies of the seabed natural gas hydrate trial production are mainly based on temperature and pressure monitoring, and the geological disaster induced by the seabed natural gas hydrate trial production monitoring technology is mainly based on pressure sensors and acceleration sensors, lacking comprehensive, long-term, automatic, real-time, synchronized, in situ observation equipment. Through the measurement of pore pressure, resistivity, and acoustics, the comprehensive monitoring and early warning system for deep-sea submarine geological disasters can obtain the dynamic changes in the engineering properties of the seabed sediments, the seabed topography, the pore pressure of the sediments, and the dynamic action of the bottom seawater. China has successfully carried out the second trial production of the seabed natural gas hydrate [53].
To fully draw on the experience of land hydrate development and foreign seabed natural gas hydrate development and provide a Chinese-style solution to the geological disasters induced by deep-sea
natural gas hydrate exploitation are important. Therefore, the establishment of the seabed geological disaster monitoring and early warning system not only provides a method for the quantitative assessment of the seabed geological disasters but also guarantees the safety of people working during the hydrate trial production.

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