Journal of Marine Science and Application (2024) 23: 617-627
https://doi.org/10.1007/s11804-024-00561-9

RESEARCH ARTICLE

Monitoring Technologies for Marine Carbon Sequestration in Zhanjiang

Yiwen Xiong[1], Yangze Dong[1], Xiahua Chen[1] and Wenchang Ling[1]

Received: 26 December 2023 / Accepted: 13 March 2024

Abstract

Marine carbon sequestration is an important component of carbon dioxide capture, utilization and storage (CCUS) technology. It is crucial for achieving carbon peaking and carbon neutralization in China. However, CO_2 leakage may lead to seabed geological disasters and threaten the safety of marine engineering. Therefore, it is of great significance to study the safety monitoring technology of marine carbon sequestration. Zhanjiang is industrially developed and rich in carbon sources. Owing to the good physical properties and reservoirs and trap characteristics, Zhanjiang has huge storage potential. This paper explores the disaster mechanism associated with CO_2 leakage in marine carbon sequestration areas. Based on the analysis of the development of Zhanjiang industry and relevant domestic monitoring technologies, several suggestions for safety monitoring of marine carbon sequestration are proposed: application of offshore aquaculture platforms, expansion and application of ocean observation networks, carbon sequestration safety monitoring and sensing system. Intended to build a comprehensive and multi-level safety monitoring system for marine carbon sequestration, the outcome of this study provides assistance for the development of marine carbon sequestration in China's offshore areas.

Keywords Marine carbon sequestration; Carbon dioxide capture, Utilization and storage (CCUS); CO_2 leakage; Monitoring technologies

1 Introduction

Ever since the Industrial Revolution, the application of fossil fuels has led to a continued increase in carbon dioxide emissions and the increasing severity of the greenhouse effect. The total greenhouse gas emission in China in 2020 was approximately 13.6 billion tons, accounting for one-third of global emissions (Zhang et al., 2021). In 2019, the United Nations Intergovernmental Panel on Climate Change pointed out the necessity to control global warming within 1.5 ℃. This climate change control target (Turgut et al., 2022) has been recognized by the United Nations and academia. Major countries worldwide have proposed their own strategies to control CO_2 emissions. China has also proposed the "3060" carbon neutrality and peak carbon strategy, with the goal of peaking CO_2 emissions by 2030 and achieving carbon neutrality by 2060. Carbon capture, utilization, and sequestration (CCUS) is currently an important technological means for achieving large-scale greenhouse gas reduction. In the short term, China's reliance mainly on fossil fuels such as oil and coal will not change. CCUS technologies can promote the efficient utilization of fossil fuels and accelerate the transformation of traditional high-emission industries, which is beneficial for China to achieve its "3060" strategic goal (Zhao et al., 2023).

CCUS refers to the process of capturing and separating CO_2 from emission sources such as energy utilization, industrial production, or air and then transporting it to suitable locations for sequestration or utilization, ultimately achieving CO_2 reduction. Its feasibility largely depends on the reliability of carbon sequestration, which mainly includes onshore geological sequestration and seabed sequestration (Li et al., 2023b). Compared with terrestrial carbon sequestration, marine carbon sequestration has the advantages of being far from habitats, surface water bodies, and groundwater layers that humans rely on for survival with higher safety and lower environmental risks (Li et al., 2023a). However, similar to resources such as methane hydrates, subsea oil, and shallow natural gas, subsea carbon sequestration also faces the threat of geological hazards caused by gas migration and leakage. Monitoring environ-mental geolog-

Article Highlights

- Establishing a safety monitoring system for carbon sequestration tailored to local conditions is necessary to ensure the safety of underwater CCUS projects.
- The risk mechanism of CO_2 leakage in underwater carbon sequestration has been analyzed, and typical monitoring technologies for subsea carbon storage in a marine environment have been summarized.
- On the basis of an overview of the Zhanjiang region and relevant domestic and foreign technologies, several suggestions have been proposed for carbon sequestration monitoring schemes.

✉ Yangze Dong
dongyangze@zjblab.com

[1] Zhanjiang Bay Laboratory, Zhanjiang 524000, China

ical hazards for potential CO_2 leaks during carbon sequestration is necessary to maximize carbon sequestration benefits and minimize disaster risks. As a typical multi-phase multi-field coupling process (Dixon et al., 2015), CO_2 leakage is complex and uncertain. Small-scale CO_2 leaks can be repaired in a timely manner. However, in the absence of a comprehensive and continuous monitoring plan, the leak expands and seriously affects the stability of the seabed, damages marine engineering facilities, and even triggers large-scale marine geological disasters such as submarine landslides, resulting in large life and property losses. Therefore, for carbon sequestration efficiency and regional security (Zhang et al., 2023), conducting a multilevel, multidirectional, and multi-cycle environmental geological monitoring and quantitative evaluation of marine carbon sequestration is necessary to ensure the safety and rationality of the entire project (Huo et al., 2014). This step must be carried out synchronously and throughout the process (Tanase et al., 2023).

In the Leizhou Peninsula, where Zhanjiang is located, the heavy chemical industry produces high CO_2 emissions above a certain scale. This region has the unique offshore natural burial conditions of China–offshore developed oil and gas fields and huge potential for subsea carbon sequestration. It also has superior conditions for CCUS projects. This work analyzes related domestic technologies based on the development of Zhanjiang's industry, proposes thoughts and suggestions on the monitoring plan for marine carbon sequestration, and helps achieve China's "3060" goal.

2 Overview and risks of marine carbon sequestration

2.1 Overview of submarine carbon sequestration

Underwater carbon sealing has been proven to be safe and effective in other countries. Norway has the earliest and most mature underwater carbon sequestration operations. As early as 1996, this country launched the CCUS project for the Sleipner oil field. As indicated in Figure 1, CO_2 generated during natural gas and oil extraction was first separated and then injected into the saltwater layer through inclined wells. The airtightness of the geological structure of the seabed saltwater layer was utilized for CO_2 storage. As the world's first commercial-scale submarine carbon sequestration project, the Sleipner Oilfield CCUS project has been in operation for over 20 years. This project stores more than 1 million tons of CO_2 annually and has recorded no abnormal activity or leakage of stored CO_2.

In addition to Norway, countries such as Denmark, Australia, and Brazil have successively launched undersea carbon sequestration projects. Sixteen CO_2 geological sequestration projects are ongoing in 9 countries and cover major

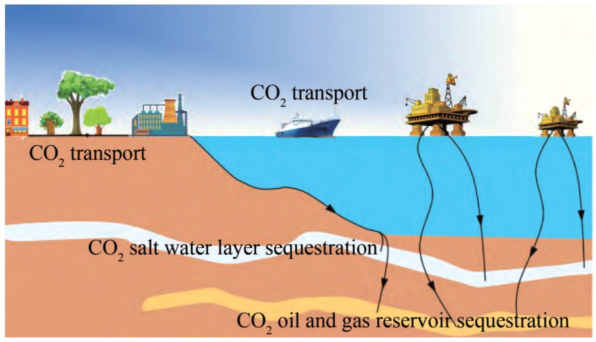

Figure 1 Schematic of marine carbon sequestration

sea areas worldwide. One of them is China's first underwater carbon sequestration demonstration project launched in 2021. The equipment was completely built by Qingdao Offshore Oil Engineering Co., Ltd. in 2022 and has been employed in Enping 15-1 Oilfield in the Pearl River Mouth Basin, South China Sea. This project separates and dehydrates the CO_2 generated by offshore oil fields and then injects it back into the saltwater layer for permanent sequestration deep in the seabed. This project is expected to store approximately 300 000 tons of CO_2 annually, with a cumulative sequestration capacity of over 1.46 million tons, equivalent to the emission reduction target achieved by 1 million cars. China has neither put forward clear environmental monitoring requirements for marine carbon sequestration nor implemented targeted environmental geological monitoring for sequestration areas. Nevertheless, the Enping 15-1 oilfield marine carbon sequestration demonstration project conducted environmental monitoring research for the first time, monitoring elements such as delayed earthquakes, formation water, environmental conditions, and reinjection parameters (Bourne et al., 2014) to fill the gap in China's regional environmental monitoring demonstration for marine carbon sequestration.

2.2 Risk of subsea carbon sequestration

In the long run, the uncertainty and complexity of the geological conditions of the seabed always lead to the possibility of slow gas leakage in the carbon sequestration area of the seabed, especially because the injection wells, formation fractures or faults, and pore paths corroded by carbonate fluids are all channels for gas leakage. Numerical simulations reveal that regardless of the form of marine carbon sequestration, a certain degree of leakage will always occur. The retention rate is between 65% and 100% after 100 years, and between 30% and 85% after 500 years (Zhang et al., 2010). Although the release of CO_2 after marine carbon sequestration is extremely slow, the risk of leakage cannot be ignored. Once CO_2 leaks, it first causes seawater acidification, thereby disrupting the balance of marine ecosystems and threatening the diversity of marine life. During this process, the activity of marine organisms, the horizontal and vertical movement of seawater, and even the geological and geomorphic features of the seabed may be affected (Rosenbauer et al., 2005). Cracks, especially in rock formations, can expand or even penetrate under high pressure and easily cause splitting failure. Stress concentration can even lead to the appearance of sliding surfaces within a rock formation, triggering a series of geological disasters such as fault activation, seabed collapse, and seabed earthquakes. CO_2 migration changes the stress of a rock formation and further exacerbates its instability through chemical reactions (Metz et al., 2005).

CO_2 leakage in the ocean inevitably causes damage to the ecological environment, but the degree is not yet clear. Safety issues resulting in CO_2 leakage throughout marine carbon sequestration must be taken seriously. The benefits and risks of marine carbon sequestration coexist. Submarine sediments have enormous carbon sequestration capabilities, but the development and promotion of marine carbon sequestration technologies are constrained by the geological and environmental safety of carbon sequestration areas (Krylov et al., 2021). The temporal and spatial spans of underwater carbon sequestration are large, the geological conditions of the seabed are complex, and the propagation methods and pathways of gas leaks are uncertain. Therefore, developing and applying targeted geological environment monitoring technologies for marine carbon sequestration areas are crucial. These technologies quantify the amount of CO_2 leakage on the seabed, accurately evaluate the efficiency of carbon sequestration on the seabed, and make emergency responses to CO_2 leakage accidents on the seabed.

2.3 Main technologies for monitoring marine carbon sequestration

The two main types of technologies for the geological environment monitoring of underwater CO_2 leakage are acoustic (quantitative estimation of bubbles) and chemical (detection and characterization of chemical anomalies in seawater). Both types are supplemented by other methods, such as ocean current meters and CTD measuring instruments. The monitoring content mainly includes marine environ-mental factors such as partial pressure of carbon dioxide (pCO_2), CO_2 plume, hydrogen ion concentration, seawater pH, and metal ion concentration. The main environmental geological monitoring technologies for marine carbon sequestration areas include relatively mature solutions, such as seismic survey monitoring, gravity monitoring, resistivity monitoring, sediment pore pressure monitoring, and seabed deformation monitoring.

2.3.1 Earthquake investigation and monitoring

Seismic survey and monitoring is one of the most widely used and effective means to investigate and monitor the distribution of seabed resources. This technology can determine the escape characteristics of fluids. Earthquake investigation and monitoring utilize the elastic differences between different media to study the propagation characteristics of seismic waves underground, thereby exploring the specific situation of underground soil layers. Through seismic exploration, we can analyze deep fault distribution, seabed geological structures, and various potential geological hazard factors. Submarine seismic survey and monitoring can be used to observe micro-seismic events caused by gas migration in carbon sequestration areas on the seabed and has been widely applied in the qualitative and quantitative research of free gases. For example, underwater seismometers in the Arctic Ocean have recorded seismic response characteristics caused by tectonic processes and methane bubble release from the seabed (Blackford et al., 2014).

2.3.2 Gravity monitoring

After being injected into the seabed, CO_2 fills and replaces the existing pore fluid in the reservoir, changing the corresponding gravitational acceleration field of the reservoir. Therefore, monitoring the spatiotemporal variation of the gravity acceleration field in the marine carbon sequestration area allows us to estimate the mass change and distribution of CO_2 after sequestration, monitor CO_2 migration on the seabed, and reveal the spatial distribution pattern of CO_2 on the seabed. Gravity monitoring is a supplement to earthquake investigation and monitoring. At present, the dynamic monitoring of marine carbon sequestration areas through gravity has been carried out using underwater robots (Stegmann et al., 2012).

2.3.3 Electrical resistivity monitoring

CO_2 leakage directly affects soil conductivity. Electrical resistivity can be used to determine the relationship between sediment physical and chemical properties and to examine permeability, porosity, and structural factors. Therefore, resistivity monitoring can infer the process of CO_2 leakage from the seabed by monitoring the evolution of electrical parameters. Germany has deployed a vertical resistivity array for monitoring CO_2 leakage in undersea carbon sequestration areas in the Ketzin CCS project and found that resistivity is highly sensitive to CO_2 saturation (Wu et al., 2020). Multiple experiments were conducted using the resistivity probe in-dependently designed and produced by the Ocean University of China, and the test results show that resistivity monitoring can determine the gas diffusion process in a certain space (Nooner et al., 2007). This technology also pro-vides a potential in-situ monitoring method for CO_2 leakage in marine carbon sequestration areas.

2.3.4 Sediment pore pressure monitoring

In addition to CO_2 injection and leakage, CO_2 sequestration influences the stress dynamic equilibrium of soil layers. Recorded by a pore pressure sensor, the pore pressure can accurately reflect the characteristics of fluid migration, characterize the external stress and internal strain of seabed rock and soil, and indirectly reflect the evolution of seabed stability through the judgment of pore pressure data. It is an important indicator for determining the possibility of submarine geological hazards. Since the emergence of NGI Illinois differential pore pressure monitoring equipment, pore pressure monitoring rods have been widely used to study the geo-logical problems caused by gas migration, such as shallow gas escape and natural gas hydrate decomposition in the seabed environment (Saleem et al., 2021). For example, the Plance pore pressure monitoring rod developed by the University of Bremen in Germany was successfully applied in mud volcano monitoring tasks from 2014 to 2016, recording multiple sudden changes in pore pressure events.

2.3.5 Seabed deformation monitoring

CO_2 leakage from the seabed can disturb the stress field in the rock formation, reduce the stability of the seabed, and ultimately lead to geological disasters such as seabed de-formation and sliding. Acoustic monitoring methods, such as side-scan sonar depth measurement and multi-beam depth measurement, have been widely used in seabed topography and geomorphology measurements. Acoustic sounding technologies can monitor seabed deformation; however, they have difficulty monitoring the deformation and sliding in real time, and the monitoring accuracy is relatively limited. With technological advancement, sensors have gradually been accepted and applied due to their long monitoring time and high data accuracy. For seabed deformation monitoring, the IFREMER SAAF inclinometer probe integrating a three-axis accelerometer was designed and developed in France (Wang et al., 2017). It has shown good application performance in underwater landslide monitoring in Nice, France. Developed by the Ocean University of China, the in-situ real-time automatic monitoring equipment for seabed deformation and sliding is equipped with a displacement sensor array, which can record dynamic seabed deformation in real time. At present, it has been successfully applied in multiple in-situ monitoring works in the Chengdao area of the Yellow River underwater delta (Chen et al., 2022). Therefore, this technology can effectively monitor the deformation and sliding of the seabed.

2.3.6 Acoustic monitoring

As the only carrier of long-distance information transmitted in the ocean, sound waves can be effectively applied to underwater monitoring. Acoustic monitoring can effectively detect gas leakage in the seabed by combining the unique acoustic characteristics of gas leakage with bubble formation, bubble wall vibration, and sound generation. Current acoustic monitoring tools for underwater gas leaks include active acoustic and passive acoustic sensors. The detection distance of active acoustic sensors reaches several kilometers, and that of passive acoustic sensors ranges from several meters to tens of meters. Owing to their low energy consumption, acoustic sensors can be deployed on the seabed for a long time. The main factors affecting acoustic monitoring include monitoring system design, operating frequency, and marine environment, such as terrain, physical obstacles, and background noise. Some acoustic devices are built with multiple receiving units to improve the effectiveness of signal processing and the signal-to-noise ratio of received signals. After the signal is received, the receiving end needs to process these raw data to obtain a clear acoustic image. This type of signal processing typically requires advanced acoustic data processing algorithms to improve signal-to-noise ratio, such as target array signal processing, recognition, and localization algorithms for automatic detection of gas leaks, including adaptive beamforming algorithms.

The active acoustic detection of seabed gases is made possible by the significant acoustic impedance difference between water and gas, which leads to the high-intensity acoustic echoes of bubbles. Active acoustic technologies for monitoring marine carbon sequestration include single-beam scanning sonar, multi-beam sonar, fish exploration sonar, side-scan sonar, synthetic aperture sonar, and seabed profiler.

Bubbles form on the seabed surface when underwater gas leaks. At the moment when the bubbles detach from the leakage hole, the uneven pressure inside and outside causes the bubble wall to vibrate and produce sound waves that radiate outward. These sound waves can be measured by passive acoustic sensors (hydrophones). However, the power of the sound waves emitted by the bubbles themselves is usually lower than that of active sound systems. Hence, passive acoustic measurements are easily affected by the background noise of the marine environment. In addition, the marine carbon sequestration area is usually large, and the assessment of high-risk areas for potential gas leaks may not be accurate. Therefore, the passive acoustic monitoring of underwater gas leaks requires high-sensitivity sensors and additional advanced signal processing algorithms to identify the acoustic characteristics of bubbles and distinguish them from the environmental background noise (Roche et al., 2021).

Passive acoustic sensors are typically manufactured with low costs, durability, and energy efficiency, making them suitable for long-term large-scale deployment on the seabed. Some methods have begun to use hydrophones to record bubble acoustic data for detecting seabed gas leaks and quantifying leakage flux and hydrophone arrays to improve the signal-to-noise ratio for monitoring bubble vibration acoustic signals and locating seabed leakage points (Leighton and White, 2012). However, the monitoring range of a single tool is usually only a few tens of square meters. One of the future development directions is to deploy multiple hydrophone arrays or underwater sensor networks in high-risk areas. The equipped hydrophones of AUVs or underwater gliders can also be used for underwater patrol recognition and monitoring and combined with active acoustic sensors only if their self-noise does not affect acoustic signal processing.

3 Suggestions for carbon sequestration monitoring in the Zhanjiang region

The development of carbon sequestration monitoring technology and the establishment of monitoring systems play a significant role in many aspects of carbon sequestration. First, comprehensively monitoring carbon sequestration in the sea-bed is beneficial to accurately evaluate its efficiency. Second, monitoring also aims to ensure safety. Once a safety hazard occurs, emergency response can be quickly undertaken before the leak, and remedial measures can be adopted in a timely manner after the leak. The monitoring and research of marine CO_2 content in China are still in the early stages. With increasing attention to this issue, the monitoring of CO_2 content in seawater will be listed as an important component of China's marine scientific research and marine carbon sequestration research (Wang et al., 2009). The selection of monitoring technology should adhere to the principles of adapting to local conditions, complementing strengths and weaknesses, highlighting key areas, fully considering the characteristics of carbon sequestration sites, evaluating potential environmental risks and geological safety issues, optimizing the monitoring technology, achieving the complementary advantages of the monitoring technology, and focusing on key areas. On the basis of the current development status of the Zhanjiang industry and the relevant technologies at home and abroad, this study puts forward several suggestions for the safety monitoring of marine carbon sequestration in the Zhanjiang region to provide a reference for carrying out China's marine carbon reduction tasks and helping achieve the "3060" goal.

3.1 Overview of Zhanjiang region and CCUS

Zhanjiang is the only prefecture-level city among the three major peninsulas in China. It occupies a single peninsula, is located at the junction of Guangdong, Guangxi, and Hainan provinces (regions), and borders the Beibuwan Gulf to the west. Zhanjiang is the main seaport for the provinces in southwest China and an important port with the shortest sea voyage from the Chinese Mainland to Southeast Asia, Oceania, Africa, and Europe. It is the prefecture-level city with the longest coast-line of 2 023.6 km in China. The mainland coastline is 1 243.7 km, the island coastline is 779.9 km, and the total sea area is approximately 20 000 km. Zhanjiang has a tropical northern monsoon climate and is constantly regulated by the oceanic climate. It was once a shallow sea area. Influenced by the Indochinese and Himalayan movements, the land was uplifted and separated from Leiqiong, forming a situation facing Hainan Province across the Qiongzhou Strait to the south. The terrain of Zhanjiang is mainly plain with a high central axis, low east-west sides, high north–south areas, and low middle region. It has the largest island in Guangdong Province—Donghai Island.

Compared with the Pearl River Mouth Basin, Zhanjiang Beibuwan Gulf Basin is closer to the coastline (coastal industrial zone) and the high emissions of its heavy chemical industry account for a large proportion. High-emission enterprises such as Baosteel Zhanjiang, Zhongke Refining and Chemical, Guangdong Electric Zhanjiang, Datang Leizhou, Zhanjiang Dongxing Petrochemical, and BASF gathered in this region, prompting an urgent need for emission reduction. The developed oil and gas fields near the coast of Zhanjiang region provide sufficient carbon sequestration capacity. The offshore burial conditions in China are unique, with superior CCUS-EOR and saltwater layer carbon sequestration conditions. To effectively solve the sustainable development problem of Lingang Heavy Chemical Industry under the "dual carbon" situation, upstream and downstream enterprises and research institutions in Zhanjiang combined the inherent advantages of near-source carbon burial and the drilling ad-vantages of CNOOC to promote the application of offshore CCUS engineering and full industry chain technology research and help this zone achieve green steel, green petro-chemicals, and green coal-fired power after 2030.

3.2 Monitoring of marine environment above carbon sequestration space

The main purpose of monitoring the marine environment above marine carbon sequestration areas is to predict the risk of CO_2 leakage and its migration distribution range. This process generally includes determining the monitoring scope and analyzing the factors that may cause geological safety and leakage hazards throughout the carbon sequestration and using them as the basis for evaluation and early warning to determine monitoring tasks and objectives. Preliminary monitoring results from multiple global marine carbon sequestration projects indicate that the likelihood of CO_2 leakage caused by marine carbon sequestration is extremely low. However, in the long run, the complexity and uncertainty of seabed geological conditions always lead to the possibility of slow gas leakage in carbon sequestration areas. As indicated in Figure 2, injection wells, formation fractures or faults, and pore paths corroded by carbonate fluids are all possible channels for gas leakage.

Gas leakage in carbon sequestration areas can increase local CO_2 content, leading to seawater acidification, changes in undersea biological com-munities, and damage to the marine ecological environment. If the amount of CO_2 leak-

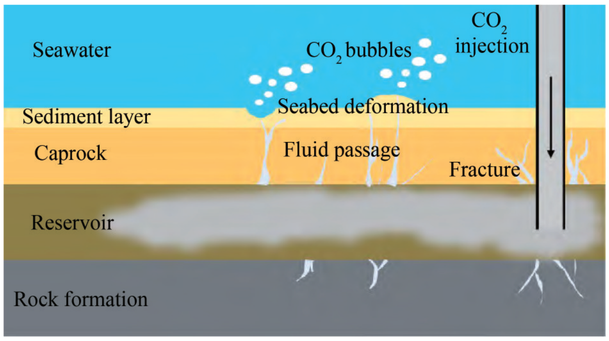

Figure 2 Changes in the marine environment above a carbon sequestration space

age is too large, then CO_2 will be released back into the atmosphere, exacerbating the green-house effect. CO_2 injection or leakage changes the stress field of the rock formation and the pore structure of the reservoir and adjacent layers, resulting in the deformation of the rock layer, affecting the permeability of the cap rock, and accelerating CO_2 leakage. Under high pressures, especially in rock layers already containing cracks, cracks can expand or even penetrate. As a consequence, splitting failure can easily occur. Stress concentration can even lead to the appearance of internal slip planes in the formation, triggering a series of geological disasters such as fault activation, seabed collapse, and seabed earthquakes. The Sleipner project in Norway simulated and calculated the stress changes in the reservoir and cap rock after CO_2 injection and sequestration. After CO_2 injection into the reservoir for 10 years, the hydraulic fracturing margin in the lower part of the cap rock is only approximately −0.1 MPa. Simulation results indicate a fracturing risk in the formation. Faults may also reactivate with the occurrence of earthquakes. CO_2 migration changes the stress of the rock formation while exacerbating its instability through chemical reactions. Indoor experimental research reveals that saturated CO_2 saline solution can change reservoir rock composition and porosity. A saturated CO_2 saline solution with low sulfate content can dissolve 10% of primary calcite in rocks and increase porosity by 2.6%. This finding indicates that excessive CO_2 leakage further leads to crack expansion and reduces the physical and mechanical properties of the reservoir, thereby shortening the CO_2 sequestration life.

3.3 Application of offshore aquaculture platforms

Owing to the vastness and complex environment of marine carbon sequestration areas, the construction of specialized environmental monitoring systems is expensive and difficult. With the scope of marine aquaculture extending from near-shore to offshore, aquaculture facilities are becoming increasingly automated and intelligent because they are being equipped with many sensors and data transmission instruments. Zhanjiang Bay Laboratory follows the development strategy of a national marine power, building a modern marine ranching demonstration city in Guangdong Province. It has laid out a series of scientific research platforms that can provide important support for monitoring marine carbon sequestration.

Figure 3 shows two types of Deep Sea Intelligent Aquaculture Platforms: Zhanjiang Bay-1and Haita-1.

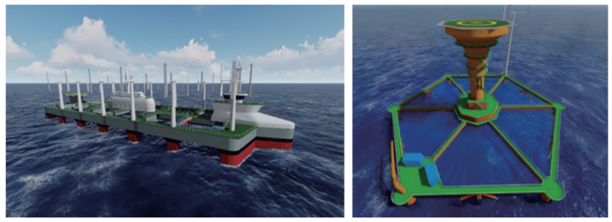

Figure 3 Two types of aquaculture platforms designed by Zhanjiang Bay Laboratory

The advantages of using a fishery-specific aquaculture platform specifically to monitor CO_2 leakage are as follows: employing professional measurement equipment, such as the existing sensors on the aquaculture platform; serving as a support platform for the safety monitoring of marine carbon sequestration; and monitoring the environment in the sea area where carbon sequestration is located, thereby reducing the cost of the monitoring system and improving its efficiency. Its shortcomings include the lack of national and industry standards for the construction, renovation, monitoring, and evaluation of marine aquaculture platforms, such as site selection evaluation standards and post-construction evaluation standards. In addition, the long-term reliability of the environmental monitoring system for marine aquaculture platforms requires testing. The application of monitoring elements and data processing can be expanded, further strengthened, and improved.

The carbon sequestration monitoring system based on off-shore aquaculture platforms relies on marine aquaculture facilities and adapts and installs existing sensors on the plat-form, integrating technological achievements such as data collection, transmission, and processing. Intelligent algorithms such as data mining, multisource data fusion, and deep learning are utilized for the data monitoring of carbon sequestration areas. As indicated in Figure 4, the architecture of a carbon sequestration safety monitoring system based on off-shore aquaculture platforms mainly includes a perception and collection layer, a data layer, a service layer, an application layer, and a support and guarantee system.

3.3.1 Perception acquisition layer

The perception acquisition layer adapts and installs existing sensors on offshore aquaculture platforms to collect environmental data related to carbon sequestration in the sea area. These marine aquaculture platforms include large-scale fishing and aquaculture factory ships, shallow-sea marine ranches, and deep-sea aquaculture cages. With the use of off-shore aquaculture platforms as information carrier

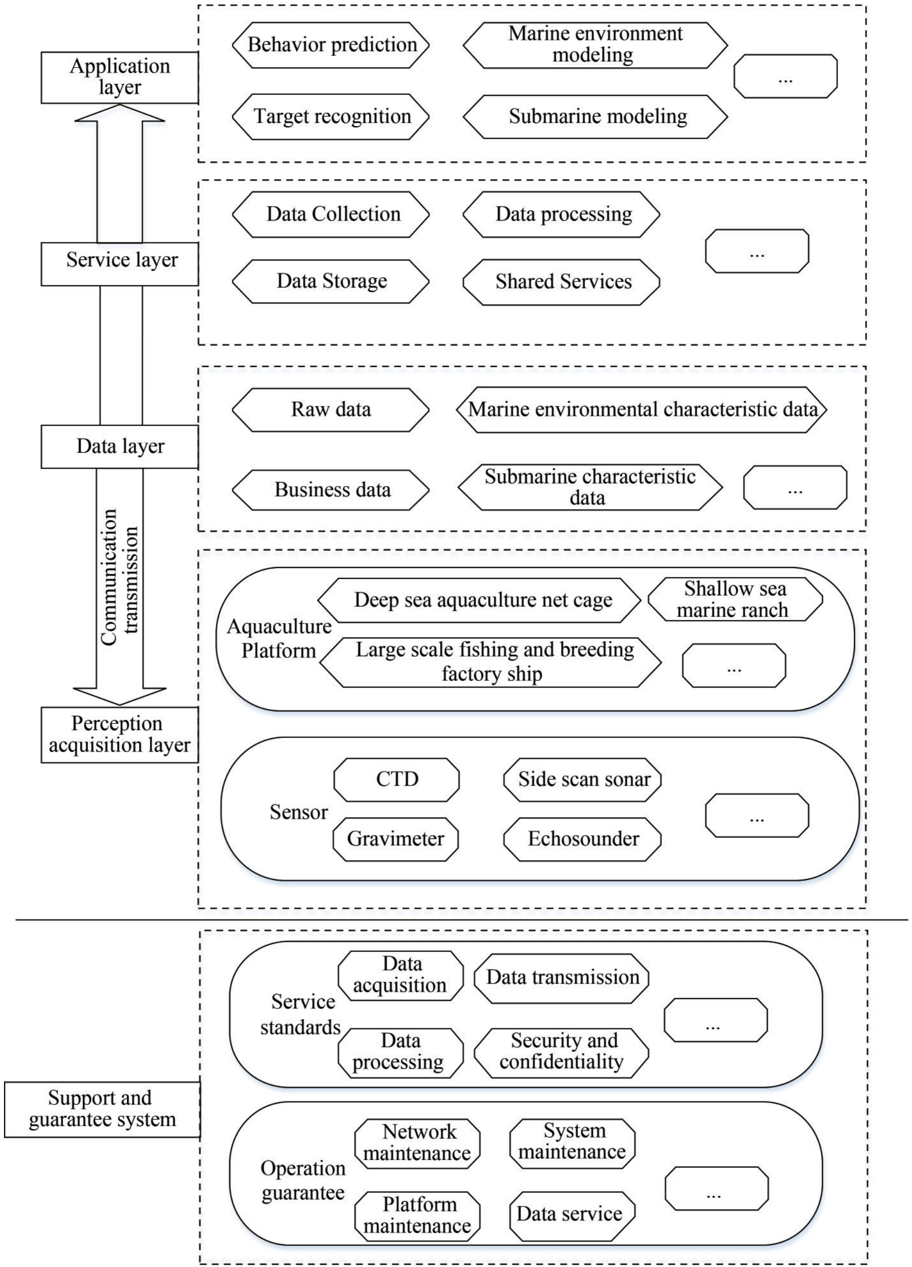

Figure 4 System architecture diagram

systems, multifunctional integration and coordinated development can be achieved for large-scale fishery and aquaculture platforms, marine environmental monitoring platforms, and marine scientific research platforms. Large offshore aquaculture plat-forms are equipped with sensors such as navigation radar, AIS, cameras, and marine environment monitoring. Depending on the task requirements, marine environmental monitoring equipment such as gravity meters, electromagnetic measurement equipment, and acoustic measurement equipment can be added to these existing sensors.

3.3.2 Data layer

The data layer needs to control the data quality of different structures, sensors, and monitoring platforms. It stores the initial data and analyzes and sorts out the data products. The data layer should also have business data that support system operation and management. Owing to the large scope, long duration, and multiple monitoring parameters of ocean monitoring, the database structure should have good scalability, be able to adapt to changes in monitoring system requirements with minimal changes and provide fast query response and data import and export services to the service layer and application layer (Hu et al., 2019).

3.3.3 Service layer

The service layer mainly includes a data collection system, data processing system, and shared service system. The data collection system implements the access collection, quality control, standardization, classification and sequestration of perception data, industry data, and external data. The data processing system realizes the analysis of multisource data. The shared service system realizes the exchange and sharing of raw and processed data.

3.3.4 Application layer

The application layer utilizes algorithms, such as data mining and deep learning, to analyze and process data. Technologies such as seabed modeling, marine environment modeling, behavior prediction, and target recognition are also employed to support the safe monitoring of marine carbon sequestration.

3.3.5 Communication transmission

Communication transmission includes three parts: maritime information transmission, shore-based information transmission, and information exchange network. The trans-mitted information includes CO_2 monitoring data and marine environmental information. In offshore areas, CO_2 monitoring data and marine environmental information can be directly transmitted back to the data processing center through shore-based communication. In the open sea, communication methods such as aerial platforms, Beidou satellites (Eide et al., 2019), and Tiantong can be comprehensively utilized to transmit ocean monitoring information back to the data processing center. As information relay platforms, marine aquaculture platforms can connect via shortwave, ultrashort wave, WIFI, wire, and LTE; receive data information from surrounding fishing vessels; and transmit the information back to shore-based data centers through satellite systems.

3.3.6 Support and guarantee system

3.3.6.1 Develop service standards

The standards and specifications of a comprehensive information service system are developed, and basic technical specifications for carbon sequestration security monitoring are provided by selecting, revising, and developing standards suitable for information collection, processing, transmission, and security confidentiality.

3.3.6.2 Establish an operational guarantee mechanism

The operation service system mainly realizes the operation and engineering support of marine basic networks and information service platforms. The operation guarantee mainly relies on the organic integration of system control technology, operation, service management processes, and operation and maintenance team resources, providing strong support for the normal operation and continuous service of the network (Wang et al., 2007).

3.4 Expansion and application of ocean observation networks

With the development of science and technology, the observation range of the marine environment extends from the sea surface to the interior of the ocean for long-term sequence measurement. Various scientific exploration instruments are deployed to the seabed to collect real-time and continuous ocean information. The ocean observation network from the acoustic monitoring system of the United States Navy during the Cold War is the third type of ocean science observation platform established by humans. Driven by new technologies such as modern sensors, the Internet of Things, submarine optical cables, underwater robots, and big data, the ocean observation network integrates multiple disciplines, such as marine geophysics, physical oceanography, marine ecology, and marine chemistry. It solves the technical difficulties of real-time transmission of ocean observation data and deep-sea dynamic transmission. It achieves all-weather, comprehensive, long-term, in-situ, continuous, and real-time observation from the seabed to the sea surface. In the past 20 years, countries such as the United States, Canada, Japan, and Europe have invested a significant amount of funds in developing underwater observation networks. Typical examples include the Canadian Submarine Observation Net-work (NEPTUNE) indicated in Figure 5, the European Sub-marine Observation Network (ESONET), the Japan Sub-marine Observation Network (DONET), and the United States Submarine Observation Network (MARS; Chen et al., 2019). In the past decade or so, China has also established a regional seabed observation network testing system in relevant sea areas.

A corresponding ocean observation network in the marine carbon sequestration area, which can include underwater and terrestrial parts, has been established. As indicated in Figure 6, the underwater part is equipped with a sufficient number of ocean observation nodes and various types of ocean observation equipment such as acoustic analyzers, CTD measuring instruments, dissolved oxygen sensors, sound velocity profilers, acoustic Doppler velocity profilers, turbidity sensors, and side-scan sonar.

Hydrological instruments and physical and chemical sensors can monitor the ocean environmental parameters of carbon sequestration areas in real time, such as pH, dissolved oxygen, salinity, water temperature, and turbidity. On shore, shore-based base stations can be established for onshore energy supply, ocean data reception and sequestration, and ocean environmental measurement data processing to collect, process, and analyze relevant marine environmental parameters; develop an intelligent monitoring plan for marine carbon sequestration safety; and provide data analysis support for marine carbon sequestration.

3.5 Carbon sequestration safety monitoring and sensing system

With the rapid development of special optical fibers and their sensing devices, optical fiber sensing technologies have been elevated. The optical fiber sensing technology

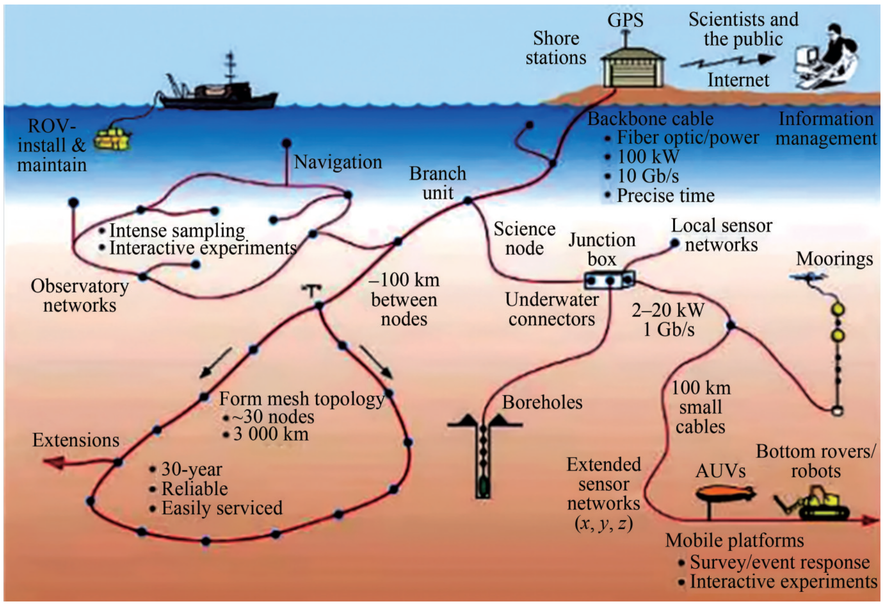

Figure 5 Network structure diagram of NEPTUNE

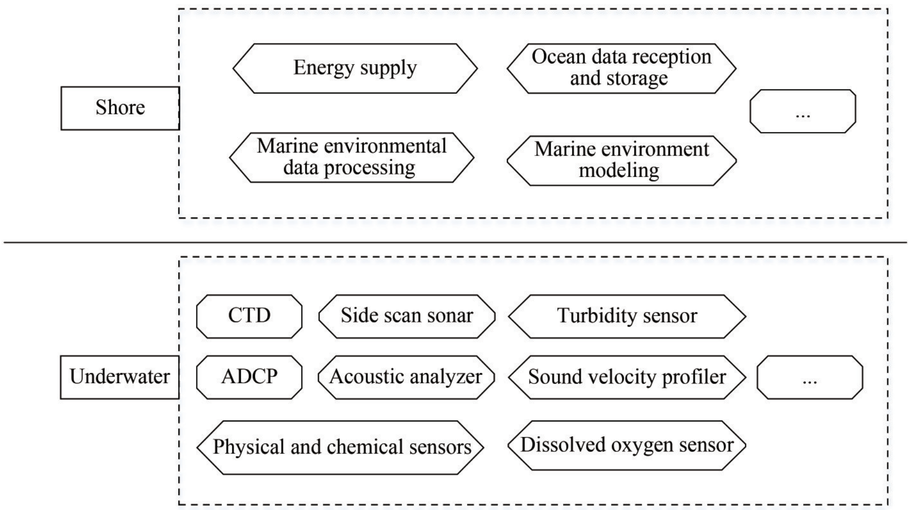

Figure 6 Expansion and application of ocean observation network

for ocean exploration and monitoring has received in-depth research from many scholars worldwide and has received widespread attention from industrial and academic communities. Fruitful research results have been achieved. The basic principle of fiber optic sensing is that the light beam incident by the light source enters the fiber optic sensor through the fiber optic and interacts with the external substances inside the sensor. The light beam becomes an optical signal modulated by the physical parameters to be measured, causing changes in optical parameters such as wavelength, intensity, frequency, polarization state, and phase. After the optical signal is fed into the optoelectronic device through a fiber optic and demodulated by a demodulator, the measured parameters can be obtained (Yuan et al., 2022). In this process, the fiber optic and its sensor components play a crucial role in signal transmission and external physical quantity perception and are an important component of fiber optic sensing. Different from long-distance communication optical fibers, the waveguide structure of the optical fiber must be specifically designed and processed into various high-precision optical fiber sensor components to sensitively perceive various external information. Fiber optic sensors use light as a carrier for sensitive information and optical fibers as a medium for transmitting sensitive information. Compared with traditional sensors, fiber optic sensors have unique advantages such as high sensitivity, good electrical insulation performance, flexible shape, strong resistance to electromagnetic interference, corrosion resistance, noninvasiveness, explosion proof, and easy remote monitoring of measurement signals.

As indicated in Figure 7, a safety monitoring and sensing system can be established for the marine carbon sequestration

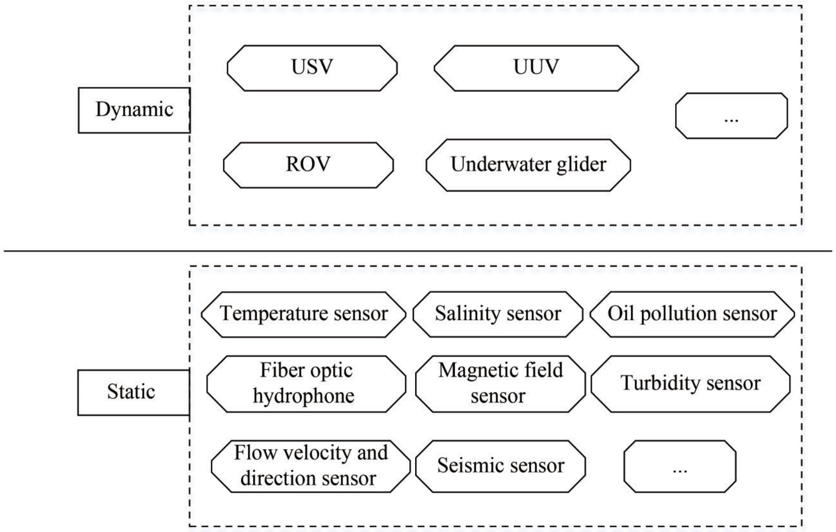

Figure 7 Carbon sequestration safety monitoring and sensing system

area based on fiber optic sensors, including ocean fiber optic temperature and salinity depth sensors, fiber optic hydrophones, ocean fiber optic oil pollution sensors, ocean fiber optic flow velocity, ocean wind fiber optic magnetic field sensors, directional sensors, and fiber optic seismic sensors.

The static monitoring to the marine carbon sequestration area is carried out through data processing and method analysis using a fiber optic sensing system to collect ocean environ-mental factors such as temperature, salinity, depth, flow velocity, seismic wave signals, metal ion concentration, and hydrogen ion concentration acoustic signals.

Although fiber optic sensors have basically reached the level of practical application, problems such as high frequency, large volume, and small dynamic range still exist. With the maturation of unmanned aerial vehicles (UAVs), new ocean exploration technologies based on these vehicles, such as UUV, USV, ROV, and underwater gliders, are constantly emerging. Owing to the advantages of UAVs, such as not relying on the mother ship for power and having a wide range of activities, strong maneuverability, and high operational efficiency, their application to an adaptive sampling net-work for monitoring the regional marine environment has become one of the current research hotspots. Some systems have been subjected to demonstration applications. Un-manned vehicles can carry relevant monitoring equipment and conduct the environmental monitoring of carbon sequestration waters based on predetermined algorithms. They can also be used for fixed-point observation operations and navigation monitoring operations within a certain range and have application advantages in extreme environmental investigations and detection, such as deep-sea hydrothermal systems. The fiber optic sensor monitoring system can be effectively supplemented with UAVs equipped with ocean sensing, achieving a system with dynamic and static integrated safety monitoring and sensing for marine carbon sequestration.

4 Conclusions

The safety of marine carbon sequestration is a focus of attention and a key factor restricting the development and promotion of this technology. Therefore, establishing a comprehensive CO_2 leakage monitoring technology system is crucial. The selection of monitoring technology should fully consider the characteristics of carbon sequestration plant sites, evaluate potential environmental risks and geological safety issues, optimize the monitoring technology to achieve complementary advantages, and focus on key areas. This work analyzes the regional overview of Zhanjiang City, determines the factors affecting the safety of marine carbon sequestration and the hazards of CO_2 leakage, and proposes several considerations for monitoring marine carbon sequestration. A collaborative intelligent monitoring technology with multiple aspects, levels, and types of disasters has been constructed. This method is suitable for quantifying CO_2 leakage, obtaining the geological information of carbon sequestration areas, correctly evaluating the efficiency of marine carbon sequestration, and facilitating emergency responses to disasters caused by CO_2 leakage. This study has practical significance for the implementation of marine carbon sequestration.

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

References

Blackford J, Bull JM, Cevatoglu M, Connelly D, Wright IC (2014) Marine baseline and monitoring strategies for Carbon Dioxide Capture and Storage (CCS). International Journal of Greenhouse Gas Control 38(1): 221-229. DOI: 10.1016/j.ijggc.2014.10.004

Bourne S, Crouch S, Smith M (2014) A risk-based framework for measurement, monitoring and verification of the Quest CCS

Project, Alberta, Canada. International Journal of Greenhouse Gas Control 26(3): 109-126. DOI: 10.1016/j.ijggc.2014.04.026

Chen JD, Zhang D, Wang X, Pan XH, Wang CN, Zhang ZL, Ge HL (2019) Research on the state-of-the-art and trends of seafloor observatory. Journal of Ocean Technology 38(6): 95-103. DOI: 10.3969/j.issn.1003-2029.2019.06.015

Chen T, Jia YG, Liu T, Liu XL, Shan HX, Sun ZQ (2022) Long-term in situ observation of pore pressure in marine sediments: A review of technology development and future outlooks. Earth Science Frontiers 29(5): 229-245. DOI: 10.13745/j.esf.sf.2021.9.30

Dixon T, Mccoy ST, Havercroft I (2015) Legal and regulatory developments on CCS. International Journal of Greenhouse Gas Control 40: 431-448. DOI: 10.1016/j.ijggc.2015.05.024

Eide LI, Batum M, Dixon T, Elamin Z, Graue A, Hagen S, Hovorka S, Nazarian B, Nkleby PH, Olsen GI (2019) Enabling large-scale Carbon Capture, Utilization, and Storage (CCUS) using offshore carbon dioxide (CO_2) infrastructure developments—A review. Energies 12(10): 1945. DOI: 10.3390/en12101945

Hu KY, Geng RT, Shen FF, Wu Q, Guo ZW (2019) Universal design method of ocean environment monitoring systems. Marine Environmental Science 38(4): 628-633. DOI: 10.13634/j.cnki.mes.2019.04.022

Huo CL (2014) Study on the potential evaluation and the storage areas of the carbon dioxide seabed storage in offshore China. PhD thesis, Dalian Maritime University, Dalian

Krylov AA, Egorov IV, Kovachev SA, Ilinskiy DA, Semiletov LP (2021). Ocean-bottom seismographs based on broadband MET sensors: Architecture and deployment case study in the arctic. Sensors 21(12): 3979. DOI: 10.3390/s21123979

Leighton TG, White PR (2012) Quantification of undersea gas leaks from carbon capture and storage facilities, from pipelines and from methane seeps, by their acoustic emissions. Proceedings of the Royal Society, A Mathematical, Physical and Engineering Sciences 468(2138): 485-510. DOI: 10.1098/rspa.2011.0221

Li JH, Li PC, Li YZ, Tong F (2023a) Technology system of offshore carbon capture, utilization, and sequestration. Strategic Study of Chinese Academy of Engineering 25(2): 173-186. DOI: 10.15302/J-SSCAE-2023.07.015

Li Q, Li YZ, Xu XY, Li XC, Liu GZ, Yu H, Tan YS (2023b) Offshore CO_2 current status and suggestions for geological sequestration monitoring. Journal of Geology of Universities 29(1): 1-12. DOI: 10.16108/j.issn1006-7493.2023008

Metz B, Davidson O, Coninck HD, Loos M, Meyer L (2005) IPCC special report on carbon dioxide capture and sequestration. Technical Report, Intergovernmental Panel on Climate Change (IPCC), Geneva

Nooner SL, Eiken O, Hermanrud C, Sasagawa GS, Stenvold T, Zumberge MA (2007) Constraints on the in situ density of CO_2 within the utsira formation from time-lapse seafloor gravity measurements. International Journal of Greenhouse Gas Control 1(2): 198-214. DOI: 10.1016/S1750-5836(07)00018-7

Roche B, Bull JM, Marin-Moreno H, Leighton TG, Faggetter M (2021) Time-lapse imaging of CO_2 migration within near-surface sediments during a controlled sub-seabed release experiment. International Journal of Greenhouse Gas Control 109(14-15): 103363. DOI: 10.1016/j.ijggc.2021.103363

Rosenbauer RJ, Koksalan T, Palandri JL (2005) Experimental investigation of CO_2-brine-rock interactions at elevated temperature and pressure: Implications for CO_2 sequestration in deep-saline aquifers. Fuel Processing Technology 86(14-15): 1581-1597. DOI: 10.1016/j.fuproc.2005.01.011

Saleem U, Dewar M, Chaudhary TN, Sana M, Chen B (2021) Numerical modelling of CO_2 migration in heterogeneous sediments and leakage scenario for STEMM-CCS field experiments. International Journal of Greenhouse Gas Control 109(22): 10333. DOI: 10.1016/j.ijggc.2021.103339

Stegmann S, Sultan N, Garziglia S, Pelleau P, Apprioual R, Kopf A, Zabel M (2012) A long-term monitoring array for landslide precursors: a case study at the Ligurian slope (western mediterranean sea). Offshore Technology Conference, Houston

Tanase D, Saito H, Sasaki T, Tanaka Y, Tanaka J (2023) Progress of CO_2 injection and monitoring of the Tomakomai CCS Demonstration Project. Proceedings of the 15th Greenhouse Gas Control Technologies Conference, Abu Dhabi. DOI: 10.2139/ssrn.3366421

Turgut M (2022) Carbon dioxide emissions, capture, sequestration and utilization: Review of materials, processes and technologies. Progress in Energy and Combustion Science 89: 100965. DOI: 10.1016/j.pecs.2021.100965

Wang PX (2007) Seafloor observatories: The third platform for earth system observation. Chinese Journal of Nature 9(3): 125-131. DOI: CNKI:SUN:ZRZZ.0.2007-03-000

Wang XN, Wang J, Wu D, Zhang SW, Li C, Zhou Y (2009) Summary of monitoring technology of dissolved carbon dioxide in seawater. Journal of Ocean Technology 28(4): 24-26. DOI: 10.3969/j.issn.1003-2029.2009.04.008

Wang Z, Jia Y, Liu X, Wang D, Shan H, Guo L (2017) In situ observation of storm-wave-induced seabed deformation with a submarine landslide monitoring system. Bulletin of Engineering Geology and the Environment 77(7): 1091-1102. DOI: 10.1007/s10064-017-1130-4

Wu JX, Guo XJ, Sun X, Sun H (2020) Flume experiment evaluation of resistivity probes as a new tool for monitoring gas migration in multilayered sediments. Applied Ocean Research 105: 102415. DOI: 10.1016/j.apor.2020.102415

Yuan LB, Tong WJ, Jiang S, Yang HY, Meng Z, Dong YK, Rao YJ, He ZY, Jin W, Liu TY (2022) Road map of fiber optic sensor technology in China. Acta Optica Sinica 42(1): 0100001. DOI: 10.3788/AOS202242.0100001

Zhang SP, Liu XL, Cheng GW, Zhu CQ, Li QP, He YF (2023) Geo-environmental hazard risks and monitoring technologies for marine carbon sequestration. Strategic Study of CAE 25(3): 122-130. DOI: 10.15302/J-SSCAE-2023.03.011

Zhang X, Li Y, Ma Q, Liu LN (2021) Development of carbon capture, utilization and sequestration technology in China. Strategic Study of Chinese Academy of Engineering 23(6): 70-80. DOI: 10.15302/J-SSCAE-2021.06.004

Zhang XH, Zheng W, Liu QJ (2010) Advances in CO_2 escape after sequestration. Advances in Mechanics 40(5): 517-527. DOI: 10.3969/j.issn.1672-9064.2008.06.005

Zhao XJ, Xiao JY, Hou JM, Wu JW, Lyu XY, Zhang JX, Liu Y (2023) Economic and scale prediction of carbon dioxide capture, utilization, and sequestration technology in China. Petroleum Exploration and Development 50(3): 657-668. DOI: 10.11698/PED.20220793