

Perspective

Electrical monitoring of subseabed CO₂ sequestration: Recent advances and prospects

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Abstract:

Subseabed CO₂ sequestration represents a critical pathway within the carbon capture, utilization, and storage strategies. This study systematically discusses the multiscale research and application progress of electrical monitoring methods in the field of subseabed CO₂ sequestration. The sensitivity of microscopic pore structures to electrical methods is analysed through laboratory sample-scale tests, and the response characteristics of electrical methods during CO₂ plume migration in complex environments are characterized through large-scale model tests. With respect to theoretical inversion models, the integration of microscopic mechanisms with macroscopic evolution is effectively achieved through the application of electrical characteristic equations. Furthermore, field-scale monitoring has demonstrated the high applicability of electrical methods in evaluating pore media transport, phase transitions, and structural integrity during the subseabed CO₂ sequestration process. Finally, this study outlines future development directions for electrical monitoring, aiming to provide a theoretical foundation and technical perspective for subseabed carbon sequestration monitoring technologies.

1. Introduction

Carbon capture, utilization, and storage are effective methods for mitigating the greenhouse effect and achieving carbon neutrality goals. Among the various strategies, subseabed CO₂ sequestration has emerged as a high-potential pathway within the carbon capture, utilization, and storage framework because of its inherent advantages. Marine sediments not only provide extensive pore and fracture spaces but also offer a natural low-temperature, high-pressure environment ideal for the long-term, high-density storage of CO₂ in liquid, supercritical or solid hydrate states. Given the combined influences of complex dynamic environments and geological activities on seabeds,

monitoring the multiphase evolution of CO₂ and the structural stability of reservoirs is a critical prerequisite for evaluating the safety and long-term reliability of a sequestration system.

Recently, primary subseabed reservoir monitoring methods have exhibited the characteristics of multiscale and multiphysics coupling, primarily encompassing geophysical exploration, in situ monitoring and laboratory microscopic characterization (Liu et al., 2023; Zhou et al., 2024). Traditional geophysical techniques (such as seismic methods) enable large-scale spatial coverage for subseabed exploration; however, they still face considerable limitations in terms of spatiotemporal resolution and dynamic continuity. Laboratory

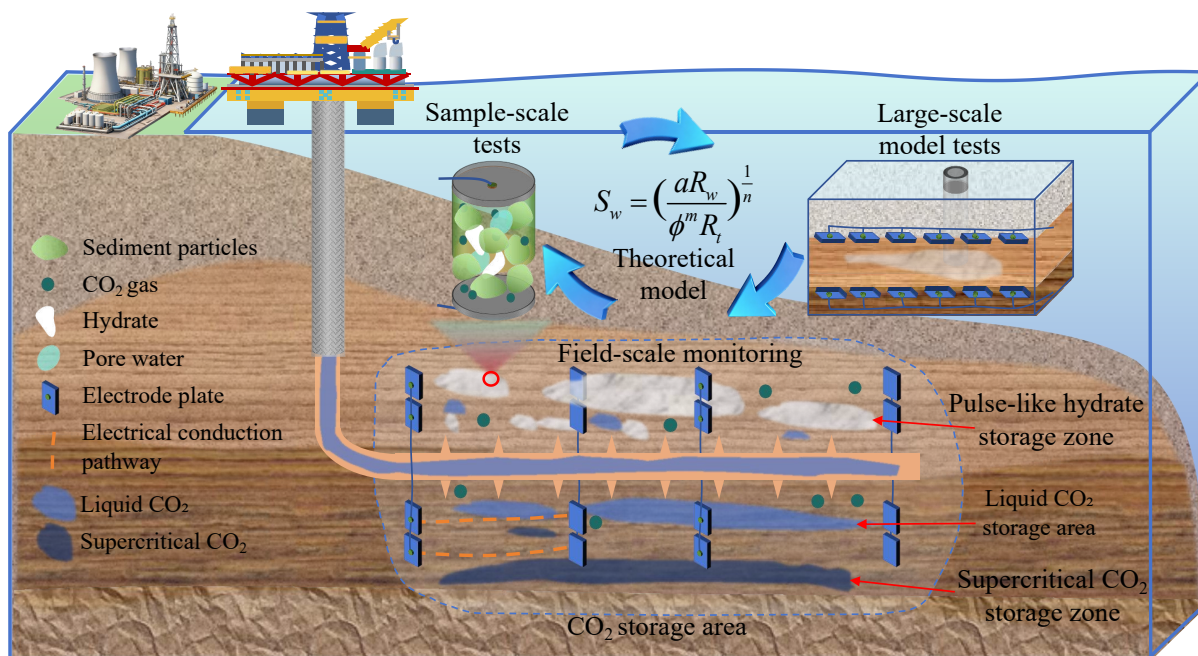


Fig. 1. Schematic diagram of subseabed CO₂ sequestration based on electrical monitoring.

microscopic experiments can reveal the microscale interactions among the “sediment skeleton-fluid-hydrate” phases; however, these experiments are hindered by challenges such as the prohibitive cost of acquiring natural cores and insufficient in situ representativeness. In contrast, in situ monitoring has demonstrated promising application prospects because it can capture real-time parameter evolution within pores across relatively large monitoring areas. Characterized by its high sensitivity to the chemical properties of pore fluids and phase transitions of pore media, electrical monitoring is considered one of the most promising technical means for achieving high-resolution dynamic monitoring (Lan et al., 2023; Cao et al., 2024). It stands as one of the few characterization techniques capable of bridging the gap between the laboratory macro- and microscales and the field scale while maintaining physical consistency (Lin et al., 2025).

This study highlights the progress of electrical monitoring in subseabed CO₂ sequestration, primarily focusing on the sensitivity analysis of electrical parameters to microscopic physical properties in sample-scale tests, electrical parameter response characteristics in large-scale model tests, theoretical inversion models, and field-scale monitoring studies, as illustrated in Fig. 1. By synthesizing unique advantages and technical challenges through multiscale analysis, this study aims to provide theoretical support and strategic directions for establishing a full-lifecycle safety monitoring system for subseabed carbon sequestration.

2. Electrical sensitivity analysis in sample-scale tests

In subseabed CO₂ sequestration monitoring, electrical methods do not directly measure the CO₂ concentration but

instead characterize the sequestration state by capturing physical perturbations within the microscopic pore environment. Laboratory sample-scale tests have confirmed that electrical methods exhibit high physical sensitivity to the evolution of the physical properties of porous media (Guo et al., 2021). Electrical research specifically targeting sequestration monitoring primarily encompasses electrical resistivity, induced polarization, and electromagnetic methods. Electrical resistivity is extremely sensitive to variations in pore fluid saturation, effectively capturing the truncation of conductive pathways caused by CO₂ displacement. In sample-scale tests, studies on electrical resistivity for CO₂ monitoring have already established a solid foundation. In contrast, induced polarization is highly sensitive to microstructural reconfiguration and interfacial electrochemical properties, showing unique potential for monitoring geochemical perturbations such as mineral dissolution, precipitation, or hydrate formation triggered by CO₂ injection. Electromagnetic methods focus on the sensitivity analysis of electromagnetic induction intensity to variations in the dielectric constant of a medium. Although current laboratory studies are dominated by resistivity techniques, multiparameter coupled sensitivity analysis provides critical data support for establishing a more robust monitoring system.

Research on sample-scale tests relies primarily on high-pressure reactor systems integrated with electrode arrays, which can accurately simulate subseabed in situ environments (Liu et al., 2018). Taking resistivity research as an example, Fig. 2 illustrates the resistivity response mechanism during pore structure evolution and briefly clarifies the ion transport mechanism. The sequestration of CO₂ within pore spaces, whether as a liquid, supercritical state or as solid hydrates, obstructs the primary pore channels, thereby increasing the tortuosity of ion migration paths. This microscale geometric

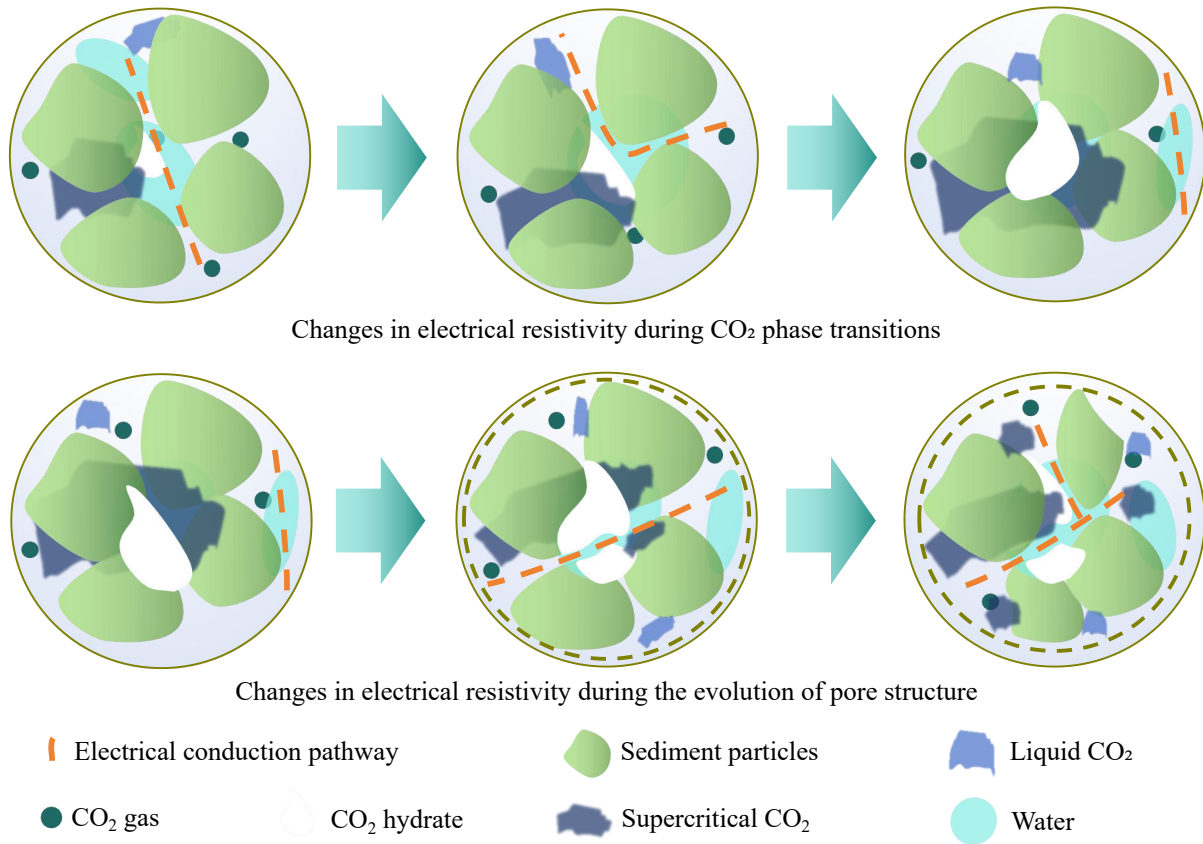


Fig. 2. Schematic diagram of resistivity response mechanisms during sediment pore structure evolution.

obstruction manifests macroscopically as a significant increase in sediment resistivity. Furthermore, pore structure alterations triggered by external perturbations may generate new ion transport channels, thereby inducing a resistivity response. Therefore, sample-scale test studies demonstrate that electrical methods are highly sensitive to mesoscopic pore structure evolution and phase transitions in porous media.

3. Electrical response in large-scale model tests

While sample-scale tests have preliminarily validated the feasibility of electrical methods for CO₂ monitoring, a considerable gap persists between the homogeneity of laboratory samples and the inherent heterogeneity of actual geological formations. The construction of heterogeneous reservoir models to characterize the nonuniform spatial distribution of CO₂ plumes and their corresponding electrical responses under large-scale conditions is critical for evaluating the engineering viability of these methods. By focusing on large-scale electrical characteristics, this approach provides essential data support for transitioning seabed CO₂ sequestration monitoring from laboratory-scale theory to field-scale application.

Large-scale model tests have demonstrated the effectiveness of resistivity in monitoring wellbore integrity under carbon sequestration conditions. Under the infiltration of supercritical CO₂, wellbore cement exhibits a linear increase in resistivity, a trend that aligns closely with the degradation of pore structures and alterations in permeability (He et

al., 2025). This sensitivity is further evidenced in aquifer injection simulations, where CO₂ significantly modulates rock resistivity. Specifically, the dissolution of calcite triggered by CO₂ injection induces an initial decrease in resistivity, followed by a subsequent increase as the chemical reaction stabilizes (Petit et al., 2021). Collectively, these large-scale model test findings provide robust evidence for the ability of electrical methods to track CO₂ plume migration and identify potential leakage pathways.

4. Theoretical models and inversion algorithms for electrical monitoring

Building upon precise studies under controlled laboratory conditions, electrical monitoring technology has demonstrated considerable potential in the real-time prediction of reservoir porosity evolution and media phase transitions (Jin et al., 2026). However, laboratory studies lack the macroscopic heterogeneity of seabed reservoirs and the complexity of the coupling between stress and electrical fields in multiple fields. To transition microscopic response mechanisms towards field engineering applications, it is essential to construct physical inversion models capable of characterizing electromechanical coupling properties. Such physical inversion models serve not only as the critical link for the multiscale shift from microscopic response mechanisms to macroscopic evolution laws but also as the core bridge connecting the intrinsic physical properties of unit cells with multidimensional inversion

characterization of large-scale formations (Constable and Stern et al., 2022).

Constructing precise resistivity characteristic equations is the foundation for interpreting the physical properties of a formation in the field of physical research. Currently, Archie's law and the Waxman-Smiths model are the two most recognized theoretical frameworks for describing the electrical response of sediments (Cai et al., 2017). As the core empirical formula for noncohesive sandy sediments, Archie's law has become the central equation for evaluating hydrate saturation through continuous refinements of the cementation and saturation exponents (Zhu et al., 2025). Conversely, for fine-grained sediments widely distributed in the deep sea, the Waxman-Smiths model introduces a cation exchange capacity to effectively correct for the interference of the electrical double layer conduction of clay minerals on pore fluid signals, thereby enhancing monitoring precision under complex lithological conditions (Merritt et al., 2016). Furthermore, when CO₂ exists as solid hydrates, the dual-water model or effective medium theory provides superior prediction accuracy by distinguishing between free pore water and clay-bound water. Comparative research indicates that the selection of a model must align with the specific lithology and phase state characteristics of the reservoir to ensure the reliability of saturation assessments.

5. Field-scale monitoring based on electrical method

In the transition from experimental stages to engineering scales, the Cranfield project, funded by the U.S. Department of Energy, has provided critical field evidence for the effectiveness of electrical monitoring. By deploying a deep cross-borehole electrical resistivity tomography system, the project successfully achieved real-time tracking of the dynamic evolution of CO₂ after injection into the reservoir (Carrigan et al., 2013; Doetsch et al., 2013). Furthermore, the Ketzin CO₂ storage pilot project in Germany demonstrated the reliability of electrical monitoring throughout the sequestration lifecycle. By utilizing a geoelectric resistivity observatory array, the Ketzin project captured a clear stepwise increase in resistivity corresponding to CO₂ injection, successfully mapping the spatiotemporal dynamic distribution of CO₂ within the reservoir (Kiessling et al., 2010; Schmidt-Hattenberger et al., 2011). On the basis of field-scale monitoring data of CO₂ sequestration, numerical modelling has revealed that the marine electromagnetic method can effectively track the evolution of a CO₂ plume at saturations less than 20% (Yilo et al., 2024; Itó and Silva et al., 2025).

The successful application in engineering of the electrical response patterns revealed in laboratory tests strongly confirms their applicability within complex geological environments. In practice, electrical monitoring has been shown to exhibit exceptional physical sensitivity in identifying phase transitions of pore media, assessing reservoir integrity, and providing early leakage warnings. It substantially compensates for the limitations of traditional geophysical methods in terms of spatiotemporal resolution and monitoring continuity.

6. Conclusions and prospects

This study provides a multiscale review of the research progress in electrical monitoring for subseabed CO₂ sequestration, spanning from laboratory microscopic mechanisms to field engineering applications. Sample-scale tests confirm that electrical methods are highly sensitive for identifying the phase evolution of porous media and characterizing the evolution of pore structures. Large-scale model tests further validate the reliability of this technology for tracking CO₂ plumes within complex heterogeneous environments. Through the integration of physical models, microscopic mechanisms and macroscopic evolution have been effectively synthesized. Furthermore, the successful implementation of field-scale monitoring projects strongly demonstrates the applicability of electrical methods under complex real-world conditions. In conclusion, electrical monitoring represents one of the most promising technological pathways for the safety assessment of subseabed CO₂ sequestration.

Electrical monitoring has demonstrated considerable potential in the field of subseabed CO₂ sequestration; however, achieving precise full-cycle characterization within complex deep-sea environments remains challenging. Currently, extensive, reliable baseline research data and engineering monitoring data from laboratory sample-scale experiments and large-scale model tests to inversion model applications and field-scale monitoring are lacking. Compared with homogeneous sediment reservoirs in the laboratory, actual subseabed sediment reservoirs exhibit complex mineralogical variations, multiscale pore structures, nonuniform compaction levels, and irregular fracture development. Consequently, the electrical characteristics of marine sediments display strong spatial heterogeneity.

Furthermore, electrical monitoring technologies generally include electrical resistivity, induced polarization and marine electromagnetic methods. Although resistivity research has achieved important laboratory milestones, studies focusing on induced polarization and marine electromagnetic methods still have considerable room for development. Given the extreme sensitivity of induced polarization to geochemical changes triggered by CO₂ injection and the effective assurance provided by electromagnetic methods for macro monitoring, future research should prioritize two key areas. First, multiscale electrical monitoring experimental investigations could be conducted under subseabed in situ conditions to capture authentic response patterns. Second, research on the joint inversion and compatibility assessment of resistivity, induced polarization, and electromagnetic methods could be further advanced. These studies help define optimal monitoring protocols for different sequestration stages and reservoir types, providing a rigorous scientific foundation for the construction of dynamic subseabed carbon sequestration monitoring systems.

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