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Perspective

Geomechanical and environmental risks in deep-sea gas hydrate exploitation: Insights from multiscale multiphysics couplings

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Abstract:
Deep-sea natural gas hydrates represent a vast energy frontier, yet commercial extraction triggers complex multiphysics couplings, posing significant geomechanical and environmental hazards. This perspective synthesizes recent advances in elucidating multiscale triggers of reservoir instability and gas leakage. Leveraging three-dimensional digital rock physics, the impact of microstructural evolution on nonlinear flow is investigated, with specific focus on hydrate morphology transitions and fines-migration-induced clogging. Geomechanical hazards are interpreted through novel stress-partitioning constitutive models coupled with acoustic-mechanical monitoring. Furthermore, the integration of multidimensional geophysical monitoring with hybrid data-driven and physics-based fusion methodologies offers a novel pathway for predicting coupled hydro-mechanical behaviors and enables real-time adaptive management. By bridging the scale gap from molecular kinetics to reservoir-scale responses, a comprehensive framework is outlined for safe and predictable hydrate production while mitigating environmental leakage risks.

1. Introduction

Natural gas hydrates represent a highly promising strategic alternative energy resource, given their immense global reserves. As extraction efforts transition toward long-term commercial exploitation, engineering and environmental challenges arises from multiscale multiphysics couplings. Extraction perturbations disrupt in-situ thermodynamic equilibrium, thereby driving hydrate dissociation. This phase transition alters microscopic pore structures and degrades macroscopic physical properties, initiating dynamic changes in fluid transport and mechanical responses within the reservoir.

Hydrate dissociation reduces sediment cementation and structural stiffness. This geomechanical alteration increases reservoir susceptibility to compaction and sand production, thereby compromising wellbore integrity. Concurrently, coupled hydro-mechanical-chemical processes alter pressure distributions, potentially allowing underlying free gas to break through the degrading hydrate stability zone. These processes create pathways for methane leakage, presenting specific environmental hazards such as artificial seafloor cold seeps. These macroscopic geohazards stem from multiscale physical mechanisms such as fines migration, dynamic pore clogging, and complex elastoplastic deformations. Mechanistic investigations and quantitative risk assessments are therefore necessitated.

Achieving sustainable hydrate production requires an in-

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Table 1. Comparison of research methods in hydrate exploitation: applicable scales, advantages, and limitations.

Methodology	Techniques	Scales	Advantages	Limitations
Experimental methods	Digital rock physics, microfluidics, triaxial shear testing	Pore to core	Direct physical evidence, high-resolution microstructural visualization, true multiphysics interactions	Pronounced scale effects, difficulty and high cost in replicating long-term in-situ conditions
Numerical simulation	CFD-DEM coupling, fully implicit hydrate simulators, stress-partitioning models	Core to reservoir	Complex multiphysics coupling, flexible parameter sensitivity analysis, long-term stability prediction	Computational bottlenecks at large scales, strong dependence on constitutive models and boundary assumptions
Geophysical monitoring	Acoustic logging, electrical resistivity, dielectric spectroscopy	Reservoir to field	Non-destructive large-scale coverage, real-time tracking of structural deformation and gas migration	Resolution constrained by depth and environmental noise, high uncertainty in multi-phase inversion
Machine learning	Physics-informed neural networks, data-driven inversion	Cross	Resolution of equation stiffness and mesh limitations, rapid real-time inversion for closed-loop control	Strong dependence on training data quality, limited generalization of pure data-driven models (physics constraints required)

tegrated analytical framework that bridges multiscale multiphysics couplings to predictable engineering responses. To reconcile scale disparities and methodological inconsistencies across current studies, the advantages and limitations of experimental, numerical, and machine-learning approaches are systematically evaluated (Table 1). An overarching framework is proposed to link microstructural evolution to macroscopic risk signals detectable through geophysical monitoring, thereby distinguishing this perspective from previous reviews. By evaluating the resolution, monitoring depth, and inversion uncertainty of acoustic and electrical techniques, the integration of these methods with production parameters is explored to form a closed-loop monitoring and control system. As illustrated in Fig. 1, this logical structure serves as the foundation for developing adaptive production strategies and early-warning systems for hydrate-bearing reservoirs.

2. Microstructural evolution and multiphysics triggers

Macroscopic geohazards and extraction efficiency are governed by pore-scale evolution and the resulting multiphysics couplings. Elucidation of these triggers is essential for predicting reservoir responses during hydrate dissociation.

(1) Pore-scale structural alteration

Micro-CT observations reveal that hydrate morphologies undergo sequential transitions during dissociation, evolving from patchy to load-bearing and ultimately to cementing structures (Wang et al., 2024a). Under reservoir compression, subsequent structural evolution is governed by the competition between strengthening and pore-filling effects of hydrate phases. This strain-dependent microstructural coupling fundamentally controls the macroscopic permeability evolution.

(2) Nonlinear flow dynamics and fines migration clogging

Fluid flow in hydrate-bearing sediments exhibits scale-dependent structural and velocity characteristics. Although macro-scale fractures can host complex non-Darcy flow, molecular dynamics simulations reveal methane migration within clay and hydrate nanopores to be dominated by nanoscale confinement effects (Zhang et al., 2025a). Concurrently, pore-scale simulations demonstrate fluid transport to induce severe throat blockages via dynamic fines migration (Cao et al., 2026). Mesoscale numerical frameworks further demonstrate accumulation and detachment of mobilized fines to be explicitly governed by the pore-to-particle size ratio and grain shape irregularity (Zhang et al., 2025b).

(3) Multiphysics coupling controls on permeability evolution

Beyond stress-induced skeleton compaction, multiphysics couplings fundamentally alter mass transfer pathways during production. A theoretical framework capturing electrochemical-mechanical coupling reveals pore-water salinity variations to alter the electric double layer of clay minerals, generating electroviscous drag that significantly amplifies nonlinear permeability attenuation under compression (Wang et al., 2026b). Concurrently, chemical disturbances promote microscopic clay swelling and skeleton restructuring in fine-grained reservoirs, resulting in permeability reduction (Li et al., 2025).

3. Engineering geohazards

The dissociation-induced phase transition fundamentally degrades the geomechanical integrity of marine sediments, rendering the reservoir highly vulnerable to structural failure.

(1) Reservoir weakening and advanced constitutive modeling

The loss of hydrate cementation redistributes mechanical loads onto the sediment skeleton. Experimental data demonstrate hydrate-bearing sediments commonly to exhibit strain-softening, whereas hydrate-free sediments typically exhibit strain-hardening (Wang et al., 2025). Furthermore, clayey-silty reservoirs exhibit time-dependent creep under sustained stress (Wang et al., 2024b). Because conventional models frequently fail to capture strain increments in the absence of changes in macroscopic effective stress, a stress-partitioning framework

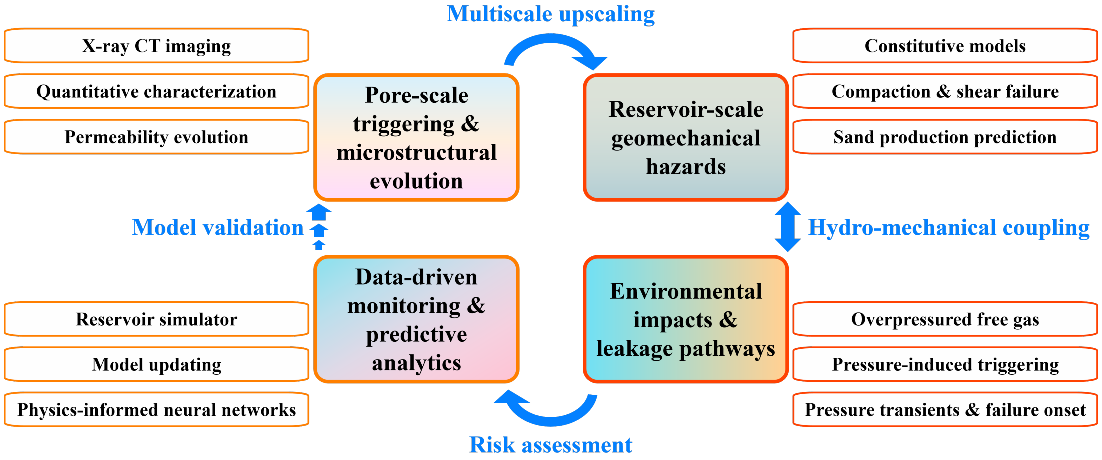

Fig. 1. Closed-loop multiscale risk framework for deep-sea gas hydrate exploitation.

has been developed (Xu et al., 2026). This framework offers a unified mathematical description of elastoplastic and creep-influenced responses, thereby enabling assessment of long-term stability and subsidence.

(2) Acoustic evaluation

Acoustic wave propagation serves as a proxy for geomechanical state characterization. Wave velocity is primarily governed by hydrate saturation during formation and by effective confining pressure during consolidation. However, the detection resolution of acoustic methods is compromise by frequency-dependent attenuation and background noise in field environments, thereby increasing inversion uncertainty.

These acoustic signatures are correlated with sand production risks. Experimental results demonstrate sand production risks to be elevated under low-confining-pressure shearing relative to the consolidation phase (Huang et al., 2026). Although acoustic-derived parameters (e.g., the dynamic elastic modulus) provide quantitative indicators for sand production, their integration requires filtering techniques to mitigate noise sensitivity. Establishment of clear thresholds for these risk signals enables optimization of well design and production efficiency.

4. Environmental risks

Although engineering geohazards threaten production infrastructure, environmental risks, particularly uncontrolled methane leakage, pose significant challenges for the commercial exploitation of marine hydrate reservoirs.

(1) Underlying gas breakthrough

Underlying free gas migration is governed by the capillary sealing capacity of the hydrate-bearing layer (Zhao et al., 2025). Experimental results indicate gas breakthrough pressure to increase with initial hydrate saturation but decrease with the pore gas-liquid ratio. As dissociation progresses, reduced hydrate saturation lowers the capillary entry pressure of sediments. Localized pressure accumulation can induce structural breaching, particularly when secondary hydrate formation temporarily obstructs flow paths, thereby creating transient overpressure conditions.

(2) Uncontrolled gas leakage

Methane leakage through the hydrate stability zone can compromise seafloor integrity and enhance methane flux into the ocean-atmosphere system (Di et al., 2026). Detection of these risk signals requires high-resolution geophysical monitoring. Acoustic methods, for instance, are effective at detecting gas plumes in the water column and impedance anomalies in the shallow subsurface. However, monitoring depth and resolution are frequently limited by signal attenuation in gas-charged sediments, and gas saturation inversion entails uncertainty arising from the multi-phase nature of the system. To mitigate these risks, monitoring data should be integrated with production parameters to establish operational envelopes, thereby ensuring that depressurization does not exceed the dynamic sealing capacity of the reservoir.

5. Intelligent monitoring

To proactively manage the engineering and environmental risks associated with deep-sea hydrate exploitation, conventional trial-and-error approaches should be superseded by intelligent, real-time monitoring and predictive management frameworks.

(1) Multidimensional geophysical monitoring

Acoustic and electrical responses serve as proxies for phase transitions and pore connectivity. Acoustic methods are sensitive to mechanical deformation, although their detection resolution in field environments is constrained by frequency-dependent attenuation and background noise, thereby increasing inversion uncertainty. Resistivity measurements capture saturation changes, although inversion accuracy is compromised by formation heterogeneity (Wang et al., 2026a). Broadband dielectric spectroscopy enables evaluation of phase distributions via the Cole-Cole model and Maxwell-Garnett mixing theory (Wu et al., 2025). Although dielectric monitoring offers high precision in saturation estimation at the core scale, its monitoring depth is limited relative to large-scale acoustic surveys. The integration of these multiscale datasets is essential to reduce prediction errors associated with localized overpressure.

(2) Artificial intelligence-driven multiphysics simulation

Physics-Informed Neural Network (PINN) architectures offer a computational framework for addressing the stiffness of governing equations in coupled problems (Huang et al., 2025). Integration of multidimensional monitoring signals with fully implicit hydrate simulators enables establishment of a closed-loop monitoring and control system. Furthermore, ensuring operational safety requires optimization of fluid dynamics. Coupled with high-performance parallel computing algorithms tailored for large-scale matrix operations, these advanced computational frameworks provide a robust foundation for real-time field inversion, adaptive production control, and proactive geohazard mitigation. Within this system, real-time geophysical data are processed to enable rapid inversion, with results subsequently used to adjust production parameters (e.g., choke pressure) to maintain the operational envelope.

6. Conclusion and perspectives

This perspective underscores that safe exploitation of deep-sea gas hydrates hinges on a comprehensive understanding of multiscale multiphysics couplings. Synthesis of advances in digital rock physics, geomechanics, and intelligent monitoring leads to an integrated framework bridging microstructural evolution to reservoir-scale stability. This framework elucidates how microscopic alterations govern nonlinear flow behavior while providing a basis for assessing risks such as subsidence, sand production, and methane leakage.

The convergence of physics-based understanding and data-driven methodologies, particularly PINNs, provides a pathway toward real-time prediction and adaptive management. Future efforts should prioritize standardized multiscale modeling and long-term field validation. Establishment of a closed-loop system integrating production control parameters with multidimensional risk signals will facilitate the transition of hydrate exploitation from experimental trials to commercially viable energy production.

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Conflicts of interest

The authors declare no competing interest.

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