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Review

A Review on Submarine Geological Risks and Secondary Disaster Issues during Natural Gas Hydrate Depressurization Production

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Abstract: The safe and efficient production of marine natural gas hydrates faces the challenges of seabed geological risk issues. Geological risk issues can be categorized from weak to strong threats in four aspects: sand production, wellbore instability, seafloor subsidence, and submarine landslides, with the potential risk of natural gas leakage, and the geological risk problems that can cause secondary disasters dominated by gas eruptions and seawater intrusion. If the gas in a reservoir is not discharged in a smooth and timely manner during production, it can build up inside the formation to form super pore pressure leading to a sudden gas eruption when the overburden is damaged. There is a high risk of overburden destabilization around production wells, and reservoirs are prone to forming a connection with the seafloor resulting in seawater intrusion under osmotic pressure. This paper summarizes the application of field observation, experimental research, and numerical simulation methods in evaluating the stability problem of the seafloor surface. The theoretical model of multi-field coupling can be used to describe and evaluate the seafloor geologic risk issues during depressurization production, and the controlling equations accurately describing the characteristics of the reservoir are the key theoretical basis for evaluating the stability of the seafloor geomechanics. It is necessary to seek a balance between submarine formation stability and reservoir production efficiency in order to assess the optimal production and predict the region of plastic damage in the reservoir. Prediction and assessment allow measures to be taken at fixed points to improve reservoir mechanical stability with the numerical simulation method. Hydrate reservoirs need to be filled with gravel to enhance mechanical strength and permeability, and overburden need to be grouted to reinforce stability.

Keywords: natural gas hydrate; depressurization production; submarine geological risks; secondary disaster; review study

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1. Introduction

With rapid economic and social development, the endless global demand for energy has led to the overexploitation of conventional fossil fuel energy, which has become unsustainable and uneconomical. At the same time, natural gas hydrate, as a kind of unconventional fossil fuel energy, is gaining more and more attention from scholars [1–3]. Under high pressure and low temperature, the gas molecules in natural gas are trapped in a cage of water molecules and form ice-like compounds. Natural gas hydrates are mainly found in plateau permafrost areas and deep-sea continental sediments. A total of 1 m^3 of gas hydrate contains about 164 m^3 of natural gas and 0.8 m^3 of water. The total carbon content of natural gas hydrate in nature is about twice the total carbon content of conventional fossil

fuel resources, which is considered the most important energy alternative in the world due to its huge reserves and high energy density [4–6]. With such abundant natural gas hydrate resource reserves, a series of feasible extraction methods have been proposed, such as the depressurization production method, the heat injection extraction method, the gas displacement extraction method, and the chemical reagent injection development method [7–9]. The validation of laboratory-scale tests proved the feasibility of these production methods. The depressurization production method has the advantages of simple operation, low cost and high gas production efficiency, and is considered to be one of the most promising extraction methods for commercializing deep-sea gas hydrates at present [10,11]. With the advancement of science and technology, depressurization production methods and their applications have been rapidly developed [12,13]. Breakthroughs have been made in the research of energy use efficiency optimization and hydrate depressurization decomposition based on artificial intelligence. Image recognition by artificial intelligence has been widely applied to hydrate reservoir prediction and experimental data analysis [14]. Many countries have successively formulated research programs on natural gas hydrates and have carried out research on natural gas hydrate production testing. The situation of marine natural gas hydrate depressurization production testing is shown in Table 1 [15–24].

Table 1. Depressurization production test of marine gas hydrate.

Production Test Area	Time	Reservoir Characterization	Production Method	Gas Production
Nankai Trough, Japan	March 2013	Water depth: 1000 m Burial depth: 300–360 m Type: Sand layer Average initial permeability: 20 mD	Depressurization production with vertical well	Cumulative: 11.9×10^4 m^3 Average: 2.0×10^4 m^3/d
Nankai Trough, Japan	May 2017	Water depth: 1000 m Burial depth: 300–360 m Type: Sand layer Average initial permeability: 20 mD	Depressurization production with vertical well	Cumulative: 26.2×10^4 m^3 Average: 0.73×10^4 m^3/d
Shenhu Sea, China	July 2017	Water depth: 1266 m Burial depth: 203–277 m Type: Muddy chalk Average initial permeability: 2.9 mD	Depressurization production with vertical well	Cumulative: 30.9×10^4 m^3 Average: 0.5×10^4 m^3/d
Shenhu Sea, China	April 2020	Water depth: 1225 m Burial depth: 207–253 m Type: Muddy chalk Average initial permeability: 2.38 mD	Depressurization production with horizontal well	Cumulative: 86.14×10^4 m^3 Average: 2.87×10^4 m^3/d

Many studies have shown natural gas hydrate plays a very important role in reservoir mechanical stability during the drilling process, and hydrate decomposition inevitably destroys the reservoir cementation, deteriorates the reservoir mechanical properties, and puts the submarine hydrate formation at risk of destabilization [25]. As pore pressure changes, hydrate decomposition and fluids output cause stress redistribution in the reservoir during depressurization production resulting in reservoir deformation and a wide-scale deformation of the submarine formation, which will lead to seafloor subsidence. Due to poor cementation in the reservoir, accompanied by a large range of plastic deformation during depressurization production, gas and water are prone to carry a large amount of sand particles during production, forming the sand production. Uneven seafloor subsidence during depressurization extraction will deform the production well in the reservoir, and sand production may lead to well clogging and damage. Production well destruction is prone to submarine gas leakage [26]. When a gas hydrate reservoir is located in a submarine slope, hydrate decompression and super pore pressure can significantly reduce the slope stability and may trigger a large-scale submarine landslide. Hydrate depressurization production may cause submarine geological risk issues, such as sand production, wellbore destabilization, seafloor settlement, submarine landslides, and potentially gas leakage risk. Hydrate-bearing sediment reservoirs and overburden are generally characterized by low permeability, so that a large amount of gas generated by hydrate decomposition during

depressurization production cannot be removed in time and accumulates in the reservoir resulting in super pore pressure in the reservoir or overburden [27]. When super pore pressure reaches the stress limit that the overburden layer can withstand, the overburden will be damaged and lead to a sudden gas eruption. Hydrate decomposition during depressurization production creates a zone of high permeability, and the hydrate decomposition zone is also a low-pressure center in hydrate formation. An osmotic pressure develops between the low-pressure center and the seawater–seafloor boundary layer, driving seawater towards the reservoir. Submarine geologic risks can destabilize the overburden and reservoir, leading to the creation of seafloor–reservoir channels. This can result in a significant influx of seawater into the reservoir and seawater intrusion. Hence geological risk issues during depressurization production are prone to a secondary disaster problem dominated by gas eruption and seawater intrusion [28–31]. Although natural gas hydrate is an important natural resource with abundant reserves, it is also an important factor affecting the stability of submarine geomechanics. Therefore, a clear understanding of the potential seafloor engineering geohazard problems during depressurization production is of great significance in ensuring environmental and production safety and avoiding secondary disasters dominated by gas eruptions and seawater intrusion, so as to efficiently develop natural gas hydrates.

Natural gas hydrate production tests have verified that hydrates can be exploited through depressurization. However, there are potential submarine geologic risks during production, such as sand production, wellbore destabilization, seafloor subsidence, and landslides. In this paper, we review the research progress of hydrate depressurization production in recent years, summarize the geological risks during production with secondary disasters, and improve the understanding of the geomechanical stability of hydrate reservoirs and the safety of the seabed environment. It is hoped that this study will provide a valuable reference for promoting the safe and efficient production of natural gas hydrates.

2. Submarine Geological Risk Issues

2.1. Sand Production

Sand production during hydrate depressurization is a complex problem involving multiple flows and geomechanical responses. The purpose of depressurization is to decompose the hydrate and collect natural gas, but the weak cementing properties of the hydrate layer cause sand and soil particles, which lose their original stability under pressure release and hydrate decomposition, to be dislodged from the sediment and enter into the production well with the fluid flow. As shown in Figure 1, under the drive of fluid flow, sand particles continue to flow out and form a continuous collapse within the reservoir. In the case of more severe sand production, reservoir subsidence around the well occurs under the action of overburden gravity [32,33]. Discontinuous deformation in the form of faults enhances the connectivity of the sediment skeleton, thereby favoring fluid flow. The increase in fluid flow rate is accompanied by the stripping of particles from the sediment skeleton, thus bringing out more sand particles. Hydrate reservoirs with small and poorly connected pore space typically have low initial permeability. When hydrate is extracted by large-scale depressurization, fluid channels are formed in the sediment skeleton, and sand particles in the reservoir are easily disturbed by fluid flow. During depressurization production, the temperature within hydrate reservoirs changes drastically, and the thermal expansion and contraction effect causes hydrates to undergo volumetric strain, which causes sand particles in formation to move and release the constraints of the sediment skeleton, and then free flow with the fluid occurs. Sand production results from the expansion of the depressurization range and the increase in effective stress in reservoirs, so that the sand grains are stripped from the skeleton due to the destruction of the sediments [34,35]. Low production pressure is commonly used in production to promote hydrate decomposition, but increased production rates can reduce the mechanical stability of reservoir sediment, leading to extensive plastic damage. As the pressure gradient and permeability increase in the reservoir, hydrate decomposition accelerates, leading to reservoir destabilization

and an increased fluid flow rate. This makes it easier for the fluid to carry sand out of the reservoir. The sand problem is typically not significant at the start of depressurization production. However, it becomes more severe with production time expansion, particularly after hydrate dissociation around the well. The sand rate is positively correlated with the initial hydrate saturation in the formation [36–39].

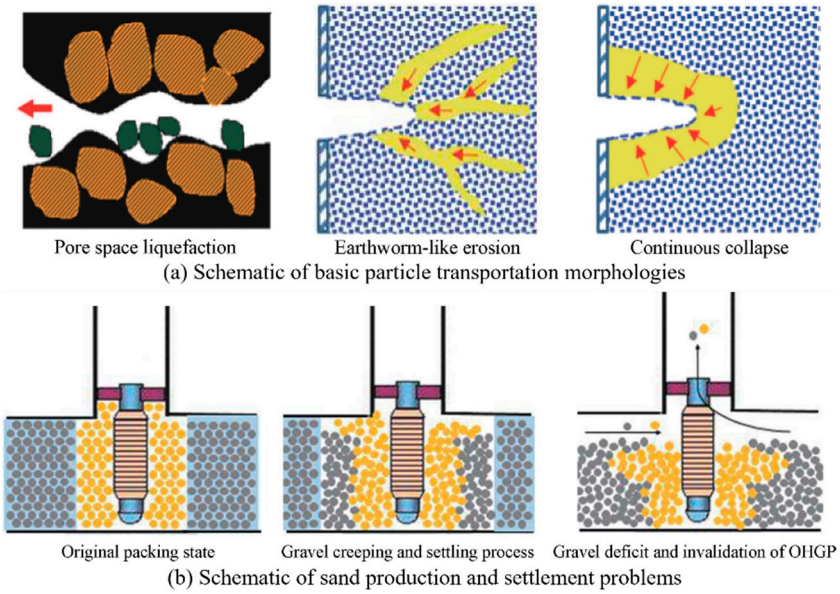


Figure 1. Schematic of the sand production and subsidence problem (cited from Li et al., 2019) [32].

Sand production is one of the key submarine geologic risks limiting the long-term and effective development of gas hydrate resources, and the behavior of sand production has attracted attention since the first marine hydrate development test in Japan was prematurely terminated in 2013 due to wellbore clogging problems caused by sand production. The second production test, at Nankai Trough in Japan, utilized a series of sand control measures to limit sand production. Production tests in 2017 and 2020 in the Shenhu Sea area did not experience wellbore plugging caused by sand outflow due to sand control measures [40–43]. The entry of sand into the production well and pipeline can cause equipment to wear out, reducing its useful life and increasing maintenance and replacement costs. This, in turn, affects overall extraction efficiency and operational stability. If sand collects inside pipelines or equipment, it can form clogs that can interfere with the smooth transportation of natural gas, or the clogs can even trigger blowouts due to pressure buildup [44–46]. The abrasion of sand particles on the equipment may lead to equipment failure and natural gas leakage, which may not only affect the safety of the personnel at the site, but also pollute surrounding environment. When sand production reaches a critical point, it can cause the formation of numerous holes and lead to continuous collapse. This can result in submarine subsidence and trigger engineering geological disasters, such as natural gas leakage or eruptions [41]. Hydrate reservoir collapse caused by sand production will easily destabilize overburden. If the amount of sand production is excessive, the reservoir may connect with the seafloor surface, leading to seawater intrusion due to osmotic pressure. It is important to take timely and effective preventive and management measures for the potential risk of sand production caused by depressurization, which requires theoretical and experimental research on the mechanism.

Simulation and experimental studies of sand production during depressurization production mainly focus on mechanism [47,48]. There are two fundamental reasons for sand production: the stress concentration and strength reduction due to hydrate decomposition. Generally speaking, the sand particle transport behavior belongs to the geomechanical control module in the theoretical model. Establishment of a multi-field coupled model that considers the geomechanical behavior is the key to simulate and study sand production

behavior [49,50]. The numerical simulation method and flow chart of sand production during depressurization production are shown in Figure 2, and its reservoir model and study method are shown in Table 2 [42–46]. Multi-field coupled governing equations for sand production typically involve sand detachment, transport, and sediment deformation, and depressurization leads to hydrate decomposition and stress concentration distribution. Depressurization results in hydrate decomposition and stress concentration distribution. Stress concentration causes particles to detach from the sediment skeleton, while fluid flow alters the multiphase fluid pressure and the temperature distribution. The main purpose of experimental studies are usually to determine sand production mechanism and investigate the relationship between sand production and pressure, fluid flow rate, sand properties [51–53]. As shown in Table 3, the model geometries and experimental methods in sand production experiments are listed, and the experimental study on sand production prevention and control is shown in Figure 3 [47–54]. The choice of the depressurization scheme and the use of sand prevention tools changes the gas production behavior. The choice of lower production pressure during depressurization production can promote hydrate decomposition and thus increase the gas production. At the same time, it will increase the risk of sand production. Sand screen tubing impedes sand transportation to the wellbore and increases gas transport resistance, resulting in reduced gas production rates. The contradiction between the stability of sand production control and efficient gas production affects the gas production efficiency of natural gas, and there is a need to explore and research more novel ways of controlling hydrate sand production during depressurization production. In addition to optimizing the depressurization method and using sand control devices, reservoir stability enhancement measures can also be used. For example, the gravel filling method enhances reservoir mechanical stability, and the chemical reagent injection method enhances reservoir cementation. On the basis of reservoir modification and the use of sand control devices, the possibility of sand stripping is reduced by adjusting the depressurization rate to ensure a relatively stable production process, and production well heating needs to be used jointly to prevent clogging of the sand control network. In order to counteract the sand stripping issue, filters or other equipment are required to separate and filter the sand particles to prevent them from entering the extraction pipelines and equipment. Monitoring equipment is required to detect sand problems during the depressurization production to ensure extraction process is conducted safely and efficiently.

Table 2. Research method and content during numerical simulation of sand production.

Reservoir Model Description	Key Control Equations for Sand Production	Main Research Content	Research Objectives	Reference
3D hollow circle	Response of permeability and porosity to sediment denudation and sand production	3D DEM fluid flow model simulation	Effects of boundary stress and fluid flow on sediment denudation and sand production	Cui et al. [42]
Rotating cylinder	Sand migration and clogging of anti-sand devices	Numerical analysis under different working conditions	Balancing sand production control and gas production	Zhu et al. [43]
2D planar symmetry model	Combined equations of control for sand stripping, transport, sediment deformation, and hydrate decomposition	Evaluation of sensitivity of sand production parameters to changes in the volume	Effect of different depressurization rates and production methods on sand production	Uchida et al. [44]
Hollow cylinder	Fluid–solid coupling calculations for sand transport	Fracture energy regularization method was implemented to diminish mesh dependency related to energy dissipation	Improve the accuracy of sand modeling	Shahsavari et al. [45]

Table 2. *Cont.*

Reservoir Model Description	Key Control Equations for Sand Production	Main Research Content	Research Objectives	Reference
Hydrate core model	Multi-field coupled model considering sand mass conservation	Incremental format solution analysis using the IMPES method and cylindrical cores	Investigating the effects of parameters such as wellbore pressure, initial hydrate saturation, and loading stress on fluid flow and sand emergence behavior	Li et al. [46]

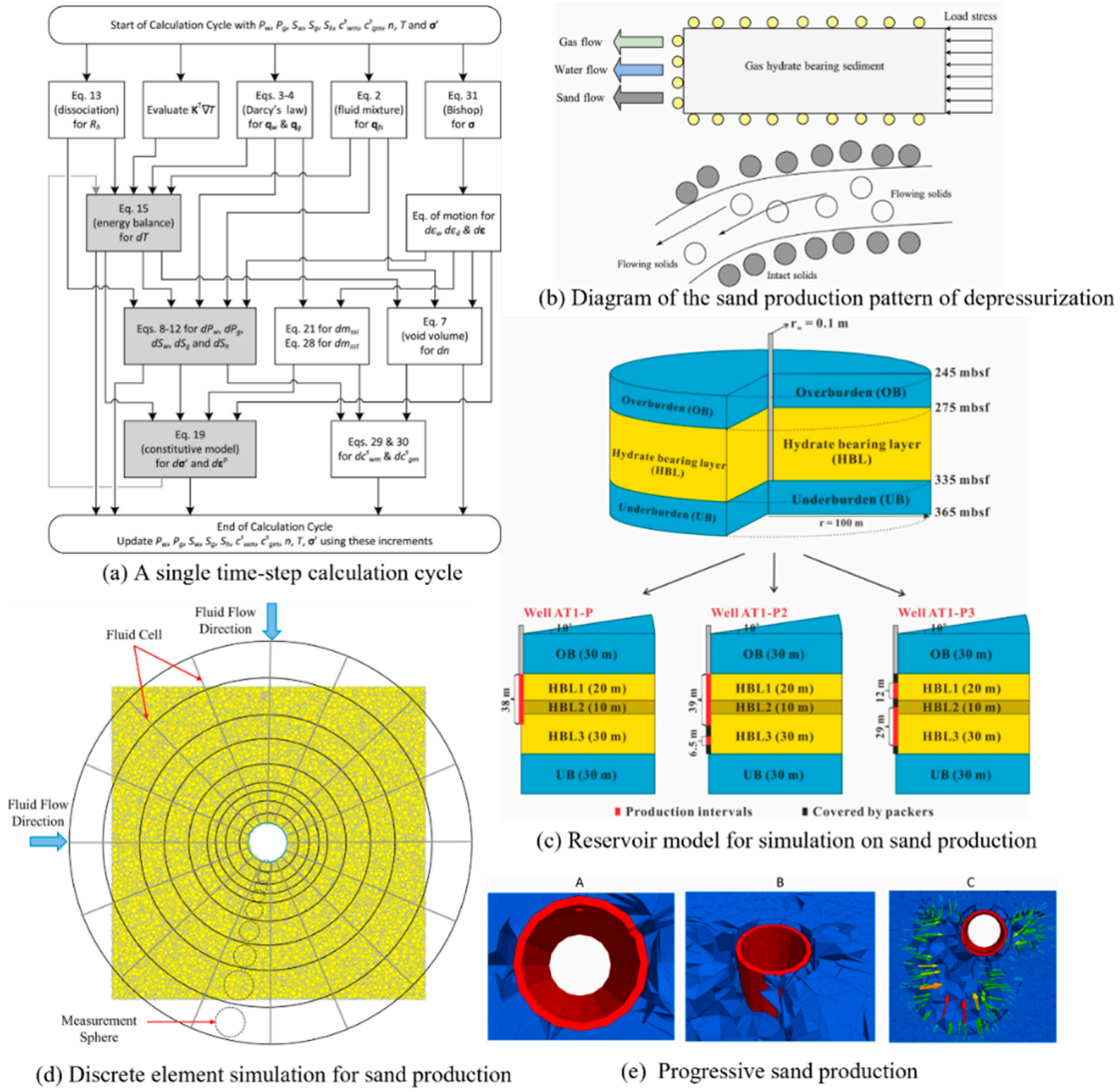
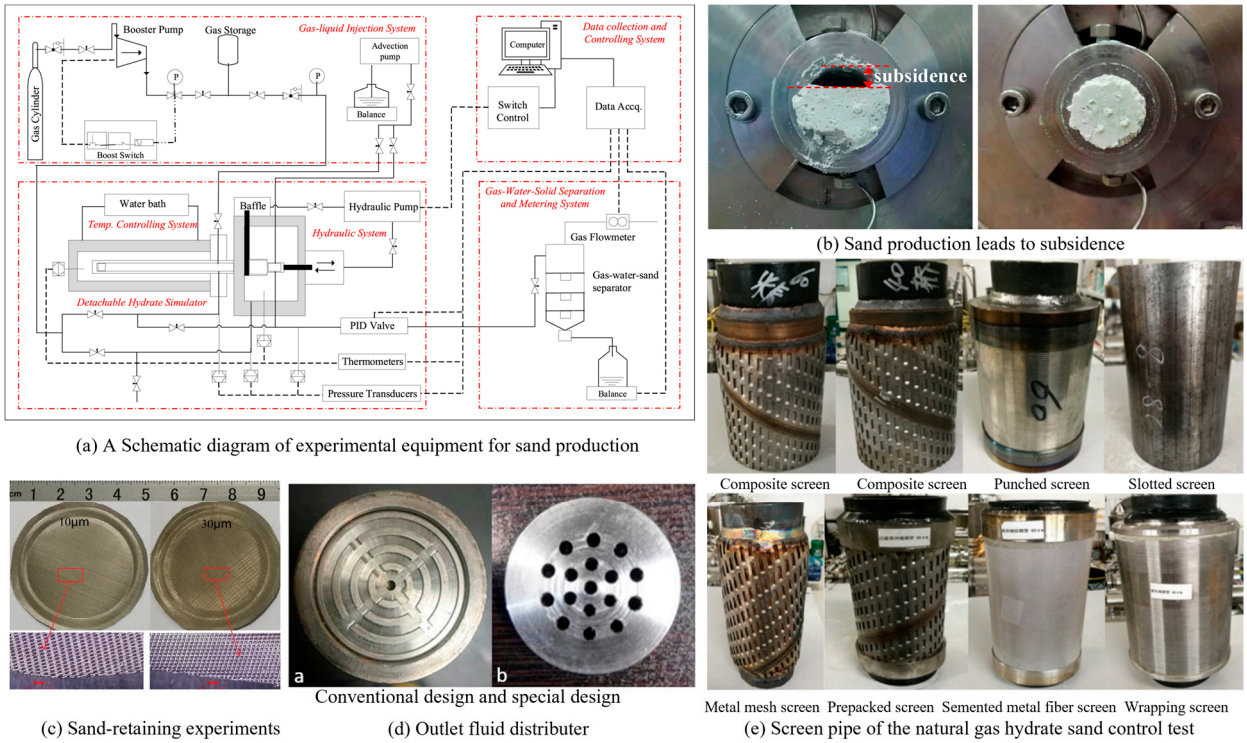


Figure 2. Method and flowchart of numerical simulation study of sand production during depressurization production (cited from Cui et al., 2016; Uchida et al., 2016; Zhu et al., 2020; Shahsavari et al., 2021; Li et al., 2024) [42–46]. A–C in subfigure (**e**) show the weak to violent sand production around well during production.

Table 3. Experimental research method and objective of sand discharge risk.

Experimental Model Description	Average Diameter of Sand Grains	Main Experimental Content	Research Objective	Reference
300 mm (D) 240 mm (L)	0.3 mm	Different overlay stresses and depressurization methods	A correction to the analytical solution for classical steady state flow	Kozhagulova et al. [47]
3.81 cm (D) 5.3 cm (L)	75 μm	Different radial to axial stress ratio conditions	Obtaining a predictive model for the mass-to-stress ratio of the discharged sand	Zivar et al. [48]
12.5 mm (L) 25 mm (D) 2.5 (H)	0.35 mm	Injection of fluid at a given pressure	Determining critical wellbore pressure for reservoir collapse	Song et al. [49]
442.3 mL (V)	27.4 μm 15.99 μm 14.45 μm 3.7 μm 4.37 μm	Different grit screen hole sizes	Analysis of gas production and sand discharge behavior with different anti-sand sieve hole sizes	Li et al. [50]
49 mm (L) 25 mm (D)	4~125 mm	Multi-channel hydration acoustic monitoring	Determining the relationship between sand output and production and designing a sand control network	Ding et al. [51]
390 mm (L) 38 mm (D)	126.4 μm	Experimentation of different anti-sand production methods	Finding effective sand control methods for hydrate reservoir development	Wang et al. [52]
50 mm (D)	15~20 μm	Clogging of sand control screen experiment	Proposed depressurization combined with wellbore heating to prevent plugging of sand control grids	Li et al. [53]



(a) A Schematic diagram of experimental equipment for sand production

(b) Sand production leads to subsidence

(c) Sand-retaining experiments

Conventional design and special design

(d) Outlet fluid distributer

(e) Screen pipe of the natural gas hydrate sand control test

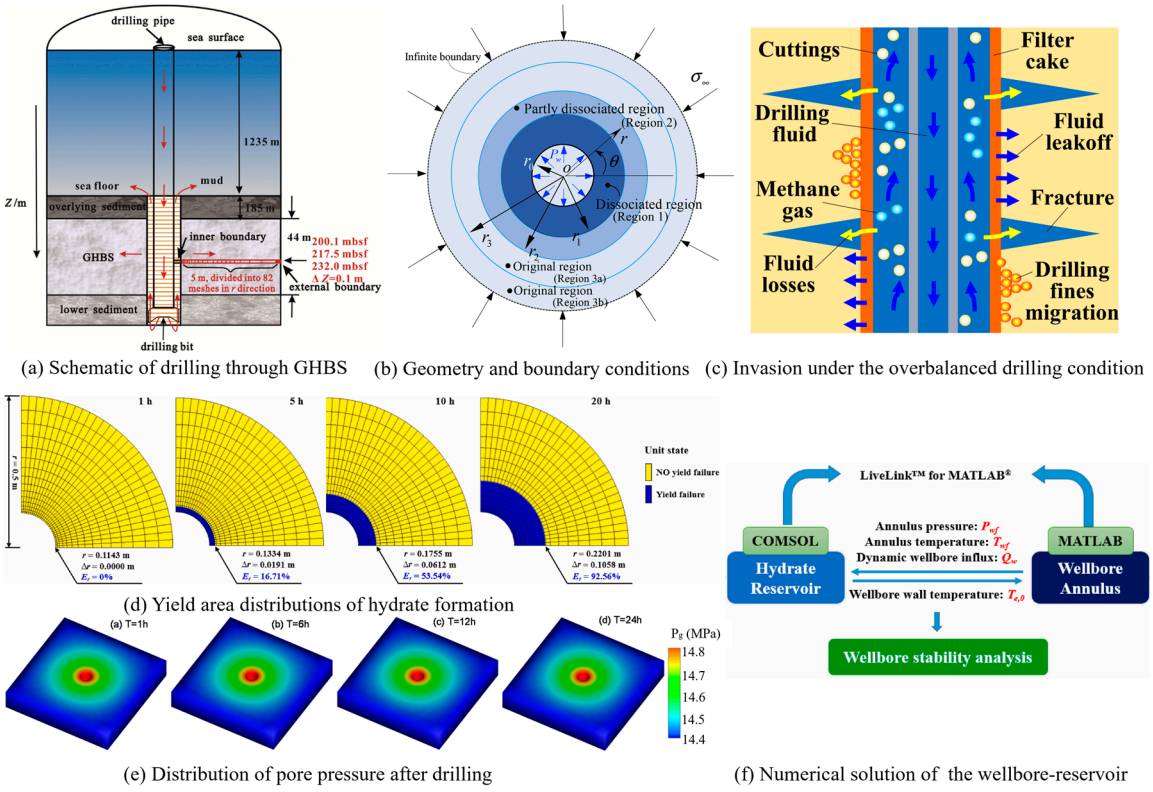
Figure 3. Experimental study on sand production risk (cited from Zivar et al., 2019; Li et al., 2022; Wang et al., 2023; Li et al., 2020; Dong et al., 2018) [48,50,52–54]. (a) and (b) in subfigure (**d**) represent conventional design and special design, respectively.

2.2. Wellbore Instability

Wellbore instability during drilling and depressurization production of marine hydrate reservoir is caused by hydrate formation conditions. If the hydrate formation is weak, prone to collapse, or contains easily dissolvable rock layers, the drilling fluid intrusion process may lead to large-scale hydrate decomposition, thus triggering wellbore instability [55–57]. Fault or fracture development in the formation is likely to accelerate the diffusion of drilling fluid and hydrate decomposition [58–60]. Poor connectivity and mobility of hydrate formation is easy to form super pore pressure gas, and high pore pressure exists in the complex special geological structure area. Drilling fluids play a crucial role in maintaining formation stability, bearing capacity, and drilling efficiency. Improper selection or use fluids can result in the loss of rock cuttings, formation collapse, or dissolution, thereby increasing the risk of wellbore instability or even gas eruption [61,62]. The construction of a well forms a channel that connects the seabed surface with the reservoir. After depressurization, osmotic pressure causes seawater to flow along the channel and into the reservoir, resulting in seawater intrusion. The risk of wellbore destabilization during the drilling process and depressurization production cannot be ignored. Hydrate decomposition can reduce the mechanical strength of the sediment surrounding wellbore, potentially causing it to reach the plastic yield state and become more susceptible to destabilization. During the early stages of depressurization production, the localized area around the horizontal well may not be fast enough to cause wellbore damage, even though it quickly reaches the yield state. From the perspective of reservoir around the well, hydrate decomposition during gas hydrate depressurization production reduces sediment mechanical strength, which may lead to a significant increase in plastic strain. From the perspective of the entire reservoir, the inhomogeneity of hydrate saturation distribution in the formation leads to the variability of reservoir mechanical strength and deformation distribution. Long-term depressurization of the reservoir can cause significant inhomogeneous deformation, leading to shear damage in the wellbore.

Sediments on the seabed that contain hydrates are typically poorly cemented and have a low mechanical strength. Drilling and depressurized production of hydrate reservoirs pose a risk of wellbore instability and damage. Wellbore damage may lead to natural gas leakage from the pipeline into the formation, polluting the surrounding environment and even threatening the safety of offshore platforms by gas eruption accidents [63]. Hydrate formations on the seafloor carry enormous formation and super pore pressures, and wellbore destabilization and damage can occur in the form of subsea gas leaks and eruptions. For example, the 2010 Gulf of Mexico well blowout triggered an oil spill that posed a significant threat to the local marine ecosystem [64]. Therefore, pressure control is a crucial task throughout the production process. Assessing wellbore stability during depressurized production is also essential. Numerical simulation methods have been utilized in many studies to address the challenges of geomechanical response, hydrate decomposition, and the coupled effects of multiple physical fields in wellbore stability analysis during drilling and depressurization production [65–69]. Establishment of theoretical models during numerical simulation needs to consider the coupling between the dynamic heat and mass transfer between the wellbore and the reservoir, the multiphase flow in the sediment, the evolution of mechanical properties and other physical fields. The drilling process accompanied by the intrusion of drilling fluids and the increase in temperature can lead to hydrate decomposition increasing the risk of wellbore destabilization [70–73]. The location of the risk of wellbore instability during depressurized production is affected by the extent of plastic damage to the sediments. The studies on wellbore instability triggered by drilling and depressurized production are shown in Figures 4 and 5, respectively. Reservoir models and simulation method used in the studies are shown in Table 4. The reservoir deformation law for long-term depressurization production of hydrate reservoir shows that the effective stress in the reservoir around the well is centrally distributed, which puts the wellbore at risk of extrusion damage [74–76]. Distribution of hydrate saturation in the formation has obvious inhomogeneity, and the reservoir is susceptible to uneven settlement. This

makes the horizontal well vulnerable to shear damage caused by uneven deformation. The consolidation degree of deep reservoir is generally higher than in shallow reservoirs, and there is a tendency for the mechanical strengths, such as Young's modulus, of hydrate-bearing sediment to increase gradually with depth. This can have a positive impact on reservoir stability when exploiting deep hydrate reservoirs, but the high stress effects of deep formations can pose a challenge to wellbore stability.



(a) Schematic of drilling through GHBS (b) Geometry and boundary conditions (c) Invasion under the overbalanced drilling condition

(d) Yield area distributions of hydrate formation

(e) Distribution of pore pressure after drilling

(f) Numerical solution of the wellbore-reservoir

Figure 4. Numerical simulation of wellbore instability problem during drilling of natural gas hydrate reservoir (cited from Wang et al., 2019; Liao et al., 2021; Sun et al., 2018; Dong et al., 2021) [66,67,70,71].

Table 4. Reservoir models and simulation methods used in the study of wellbore instability risk problems.

Hydrate Reservoir Model	Key Theoretical Models	Main Research Contents	Research Objectives	Reference
Simplified 2D axisymmetric wellbore modeling	A drilling model considering the degradation of reservoir mechanical properties due to hydrate decomposition	Elastic-plastic intervals of reservoirs obtained by closed-form solutions of computational mechanical fields	Exploring the mechanism of the reduction of drilling fluid temperature, pressure, and elastic modulus in the decomposition zone on wellbore stability	Wang et al. [66]
Plane strain model	Consider dynamic heat and mass transfer between the wellbore and the reservoir	Elasto-plastic analysis of wellbore during drilling process	Analyze the heat and mass transfer law between wellbore and reservoir and the mechanism of wellbore yield damage behavior	Liao et al. [67]
Simplified 2D axisymmetric wellbore modeling	Considering the reduction of formation stiffness and strength after hydrate dissociation	Elasto-plastic analysis of wellbore during drilling process	Analysis of the mechanical response of wellbore in elastic-plastic formations and summarization of the destabilization mechanism	Guo et al. [68]

Table 4. *Cont.*

Hydrate Reservoir Model	Key Theoretical Models	Main Research Contents	Research Objectives	Reference
Symmetric plane strain model	A theoretical model to characterize the deformation field using rock mechanics theory	Elasto-plastic analysis of wellbore during drilling process	Summarize the major influences on wellbore and hydrate formation instability	Zhang et al. [69]
Simplified 2D axisymmetric wellbore modeling	Considering the effects of drilling mud intrusion and pore water salinity	Elasto-plastic analysis of wellbore during drilling process	Guidance for the design of drilling fluids based on elasto-plastic distribution laws	Sun et al. [70]
3D reservoir model	Development of a three-dimensional multi-field coupled model describing drilling fluid intrusion	Dynamic response of drilling fluid intrusion processes and reservoirs	Characterizing the reservoir response to drilling fluid intrusion in conjunction with hydrate decomposition	Dong et al. [71]
2D planar reservoir model	Improvement of elasto-plasticity intrinsic model based on the saturation of hydrate and ice in the pore space	Analyzing the yielding of the wellbore and reservoir around the well during depressurized production in horizontal and vertical wells	Predicting stress concentrations and yield zones in wellbores and reservoirs during mining	Rutqvist et al. [72]
Simplified 2D axisymmetric wellbore modeling	A model considering the evolution of the plastic zone due to changes in temperature and pressure fields	Analyzing the effect of gas hydrate decomposition on wellbore stress and plastic zone distribution	Providing a theoretical basis for wellbore design from a mechanical point of view	Li et al. [73]
2D planar reservoir model	Consideration of multi-field coupled models based on consolidation theory	Effective principal stress concentration distribution and its stress path analysis	Prediction of stress field evolution and wellbore stability during the mining process	Yuan et al. [74]
2D planar reservoir model	Theoretical modeling of the Mohr–Coulomb criterion combined with multi-field coupled models	Mechanical behavior of hydrate reservoirs and wellbores during one year of production	Predicting deformation characteristics of producing wells due to hydrate decomposition	Sun et al. [75]
Multilayer hydrate reservoir modeling	Theoretical models considering coupled fluid and geomechanics	Effective principal stress concentration distribution and its stress path analysis	Geomechanical response and reservoir stability analysis around wells under coupled effects	Dong et al. [76]

With the help of numerical simulation method, the risk areas of geomechanical response of gas hydrate reservoirs can be assessed and predicted, so that corresponding preventive and control measures can be taken when designing hydrate depressurization production methodology. There is a transient heat transfer model between the wellbore and the sediment during drilling, which requires numerical simulation based on its thermodynamic stability and gives an optimized drilling method. Numerical simulation can be used to predict the extent of plastic damage in the reservoir and the location of the wellbore instability risk when designing and exploiting, corresponding to which the method of enhancing the mechanical properties of the reservoir and the wellbore protection measures can be taken. At the initial stage of well construction, a solid plugging agent or cement slurry is injected around the wellhead to reinforce the well wall and fill the possible leakage gaps, so as to improve the sealing and stability of the wellbore. Pressure balancing measures are used during production to maintain the balance of pressure inside and outside the wellbore, reduce the impact of changes in formation pressure on the wellbore. It is also necessary to implement a regular wellbore inspection and maintenance program to monitor the condition of the wellbore and repair or replace any possible damage in a timely manner to maintain the stability of the wellbore. Measures to plug and seal the wellbore after production is completed are taken to avoid possible leakage or pressure imbalance and to prevent environmental contamination or damage to the wellbore.

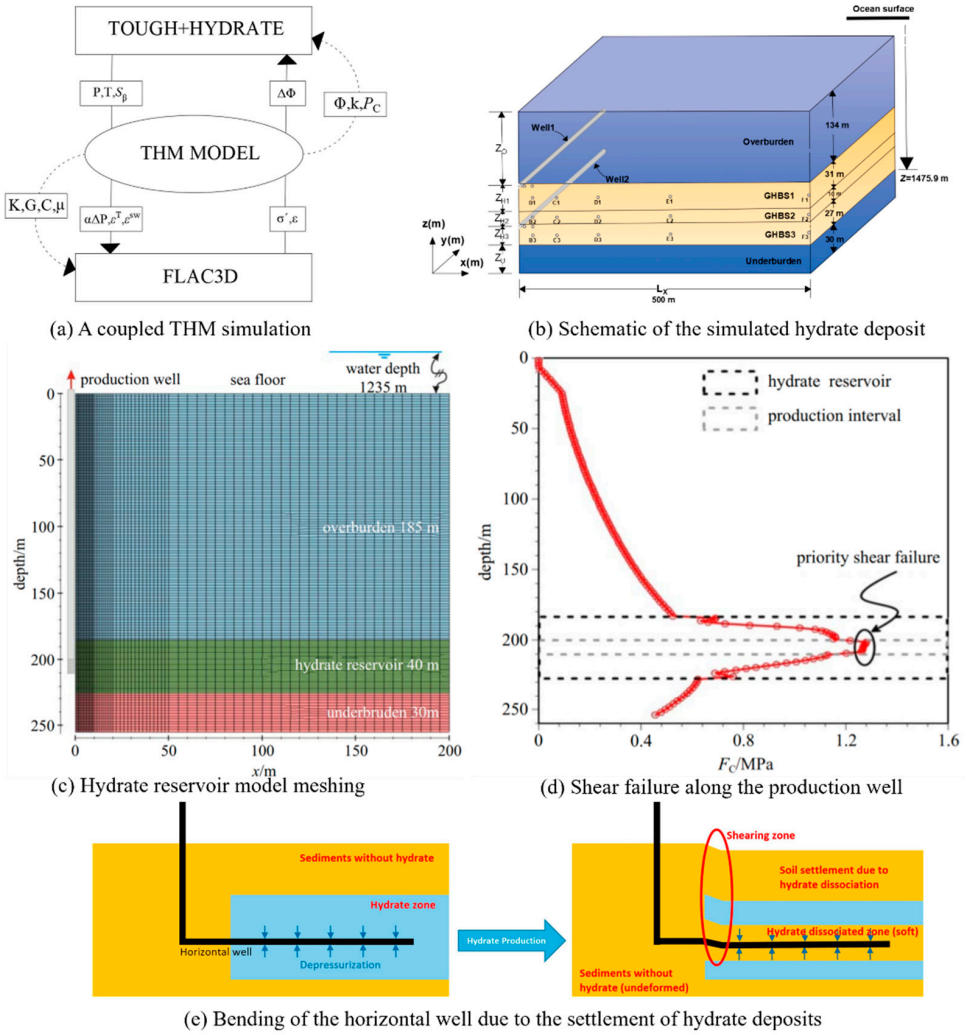


Figure 5. Numerical simulation study of wellbore instability problem during depressurization production (cited from Yuan et al., 2020; Sun et al., 2019; Dong et al., 2022) [74–76].

2.3. Seafloor Subsidence

Marine natural gas hydrate is shallowly buried in the formation, and overburden is dominated by low permeability clays, which do not have a dense and hard rock structure. Hydrate-bearing sediment is poorly cemented, and hydrate decomposition leads to a significant reduction in the mechanical strength of the reservoir, and the range of the reduction will continue to expand with hydrate decomposition [77–79]. Depressurization causes the hydrate in the sediment pore space to decompose into natural gas and water. The compressibility of fluid is much larger than that of solid hydrate, so the pore space of the sediment is compressed under the action of overburden gravity and seawater pressure, which deforms the entire hydrate reservoir. A low pressure region may form in the reservoir, causing a redistribution of internal pressure combined with ongoing gas and liquid recovery, which increases the effective stress in the formation. The range of influence of the effective stress expands over time as hydrate extraction continues. Continuous discharge of fluids in the hydrate reservoir causes the overburden to lose its support, and produces deformation and subsidence in the seafloor surface under the action of seawater pressure. From the mechanical stability analysis of the hydrate formation, the main cause of subsidence is the compression of sediment pore space during the depressurization process, so the main manifestation of subsidence is the compression and deformation of the seafloor surface [80,81]. The process of sediment compression and seafloor subsidence causes internal compaction of the hydrate reservoir, which alters the physical properties

of the formation and can impact the sustainability of gas production [82,83]. Overburden stability is disturbed by the uneven settlement of the seafloor causing sediment damage, and seawater pushes through the overburden into the reservoir in large quantities under the action of osmotic pressure. Decompression causes stress to concentrate around the wellbore, resulting in significant sediment compression and seafloor subsidence in the area surrounding the vertical well. Additionally, it causes extensive seafloor subsidence in the upper area of the horizontal well [84–86]. Seafloor subsidence can affect the stability of facilities such as submarine pipelines and cables, and increase the cost of extraction. The inhomogeneity of hydrate distribution leads to uneven reservoir deformation and seafloor subsidence, resulting in wellbore shear damage that triggers gas leakage and thus contamination of the seafloor environment.

As shown in Figure 6, research methodology for settlement risk problem is dominated by numerical simulation. From the studies of long-term depressurization production, the seafloor subsidence can reach several meters, as shown in Table 5 [72,87–91]. Seafloor settlement is different in different case studies, indicating that the seafloor surface settlement behavior is related to the mechanical properties of hydrate formation and production scheme. When hydrate formation is subjected to mechanical constraints, the vertical strain is much larger than the horizontal strain. Although the reservoir pressure drops very rapidly, the subsidence is gradual over time [88,89]. Overburden and underburden are compressed by seawater gravity and geostatic stresses, respectively, and move in the direction of the production wells, resulting in seafloor surface subsidence and underburden uplift. Seafloor surface subsidence with pore pressure reduction and the low mechanical strength of weakly cemented sediments make the seafloor surface subsidence behavior highly sensitive to production pressure. Seafloor subsidence involves the complex mechanical behavior of hydrate-bearing sediments during depressurization production [90,91]. Therefore, in addition to numerical simulation assessment there is a need to study the relationship between hydrate decomposition and reservoir mechanical properties through triaxial tests to improve the understanding of seafloor subsidence problems [92–95].

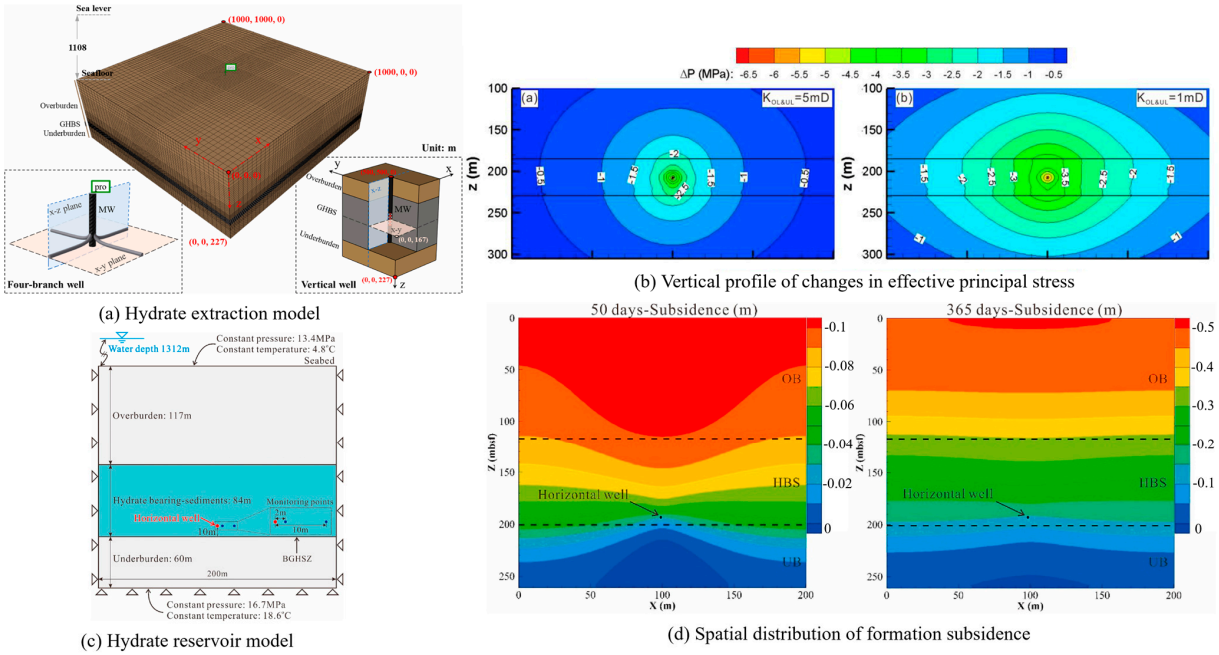


Figure 6. Numerical simulation of seafloor subsidence risk issues (cited from Jin et al., 2018; Zhang et al., 2023; Yuan et al., 2021) [89–91].

At present, the world has not carried out long-term large-scale depressurization production of natural gas hydrate. In 2020, in the Shenhu area of the South China Sea, a 30-day hydrate production test was carried out; the test used included the "four-in-one"

on-site real-time monitoring research method, as shown in Figure 7 [17]. Using a variety of technical means such as hydrate reservoir temperature monitoring, seafloor sediment pore pressure monitoring, seafloor natural gas leakage, seafloor stratigraphic stability monitoring (subsidence and landslide), full-profile seawater environmental monitoring, and water–gas–methane exchange flux monitoring of the production test platform and the surrounding area, we carried out all-around environmental monitoring from the seafloor to the middle seawater up to the sea level, and objectively evaluated the environmental impacts of the depressurization production of natural gas hydrates. From the mechanical nature of hydrate-bearing sediments, the seafloor subsidence issue in long-term production of gas hydrate is difficult to avoid. It is necessary to consider the balance between hydrate formation stability and gas production in order to design the optimal production program. Appropriate measures to improve the mechanical properties of the seafloor surface, such as overburden injection and reinforcement methods, can be taken prior to hydrate extraction. The numerical simulation method can be used to assess the stability of hydrate formation and predict potential hazard problems that may occur.

Table 5. Behavior of seafloor settlement during depressurization production.

Site	Production Time	Wellbore Selection	Seafloor Subsidence	Reference
Gulf of Mexico, Mexico	2 years	Depressurization through a horizontal and vertical well	4.5 m (horizontal well) 2.3 m (vertical well)	Rutqvist et al. [72]
Eastern Nankai Trough, Japan	6 days	Depressurization through a vertical well	15 cm	Uchida et al. [41]
Eastern offshore India, India	90 days	Depressurization through a vertical well	1.7 cm	Lin et al. [88]
SH2 drill hole, South China Sea, China	2 years	Depressurization through a horizontal well	2.5 m	Jin et al. [89]
South China Sea, China	2 years	Depressurization through a vertical well and a four-branch multilateral well	1.2 m	Zhang et al. [90]
South China Sea, China	1 years	Depressurization through a horizontal well	0.5 m	Yuan et al. [91]

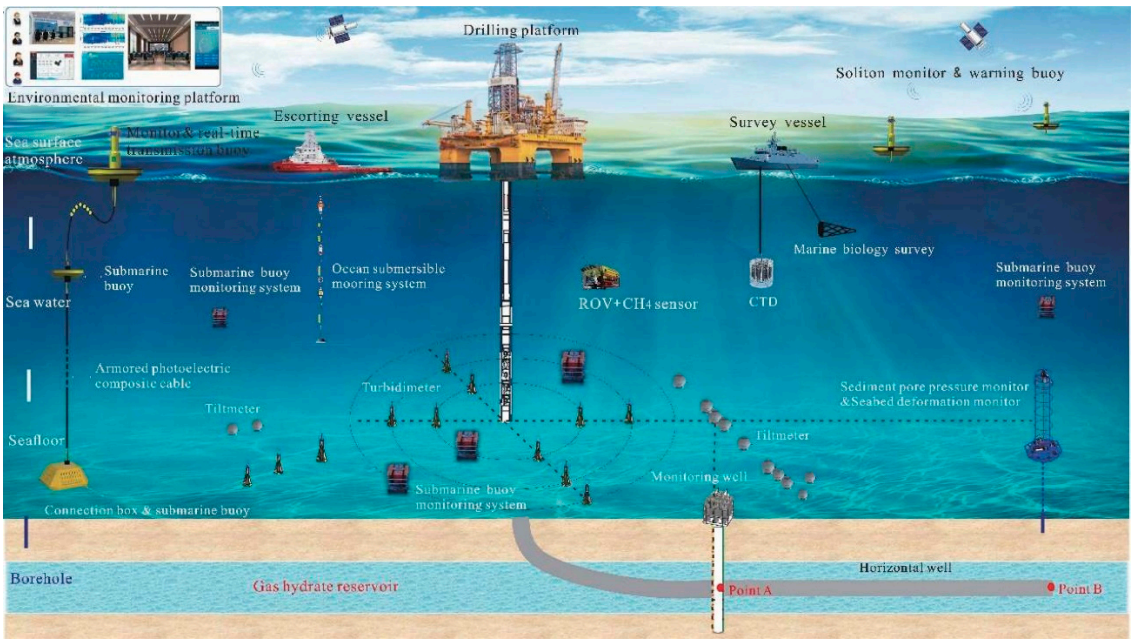


Figure 7. "Four-in-one" real-time on-site monitoring system (cited from Ye et al., 2020) [17].

2.4. Submarine Landslide

Natural gas hydrate is abundantly stored in the submarine slope, and the factors that cause submarine landslides in hydrate formations can be categorized into natural environmental factors and anthropogenic factors [96,97]. Natural environmental factors mainly include the natural hydrate decomposition caused by global warming, and anthropogenic factors are mainly the temperature and pressure perturbation of hydrate reservoir caused by hydrate extraction. Continuous deposition of sediment decreases overburden permeability, increases hydrate saturation and weakens reservoir permeability, and overburden permeability is much lower than reservoir permeability. Capacity enhancement method such as depressurization and heat injection can promote hydrate decomposition to generate large quantities of gas, but in low-permeability reservoir gas are difficult to produce in a timely manner from production well. If a large amount of gas and liquid generated by hydrate decomposition cannot be discharged in a timely manner, super pore pressures will be generated between the reservoir and the overburden. Hydrate decomposition decreases the mechanical strength of the reservoir, and the super porous pressure gas collects in the slope, which makes the submarine slope more unstable [98,99]. Seawater warming due to global warming induces widespread decomposition of hydrate reservoir, releasing large quantities of methane gas. Strong load and high temperature fluid from earthquakes and volcanic eruptions can cause shear or tensile damage to seafloor slope and hydrate decomposition, resulting in large impact damage to the seafloor environment. During hydrate extraction, different extraction method directly and significantly affects seafloor settlement and seafloor slope stability [100,101]. When a horizontal well is used to depressurize the extraction method to improve the decomposition efficiency of gas hydrate and obtain higher production, it will cause a wide range of deformation in the hydrate reservoir, especially when the hydrate reservoir is in the seafloor slope, it is easy to cause the mechanical instability of the slopes. Long-term and large-scale gas hydrate extraction poses a potential threat to the stability of the seafloor surface, especially to the hydrate slope stratigraphy [102,103]. Hydrate production causes overburden and reservoir deformation to slide toward the production well, which can trigger a submarine landslide. Large-scale submarine landslides can separate the hydrate reservoir from the overburden, resulting in direct exposure of the reservoir to seawater, which can lead to widespread hydrate decomposition and natural gas leakage [104,105]. They not only cause natural gas leaks, but also damage deep-sea oil and gas wells and pipelines, threatening the safety of the undersea environment.

Hydrate decomposition is one of the key factors for inducing a submarine landslide, and natural factors and anthropogenic perturbations induced seafloor landslides, and the on-site monitoring systems are shown in Figure 8 [106,107]. Geological records show that the increase in seafloor temperature leads to hydrate decomposition and destroys the cementation between gas hydrate and seafloor slopes, destabilizing the slopes. The historically famous Storegga submarine landslide and the Amazon Fan failure, which occurred on the Norwegian continental margin in the northeastern Atlantic Ocean, have been attributed to hydrate decomposition [108,109]. When gas hydrate is endowed in inclined reservoirs, the decomposition of hydrates will cause a weakening of the mechanical strength of the reservoir, and the inability of gas to be discharged in a timely manner may generate pore pressure buildup, inducing submarine slope instability [110–112]. Current research on natural gas hydrate formation landslides is dominated by numerical simulations and field observations, which often increase reservoir instability when production enhancement measures are planned to increase natural gas production, which requires mechanical characterization of submarine slopes during depressurization production to fully understand the potential geomechanical response issues that come with increased production [113,114]. A numerical simulation study of the seafloor landslide risk in the hydrate formation is shown in Figure 9, and a study on the hydrate extraction scheme and seafloor slope destabilization mechanism is shown in Table 6. The average inclination angle of hydrate reservoir in the South China Sea is approximately 3.3 to 3.6°, and the maximum angle reaches 25° [114].

The destabilization of seafloor slopes induced by artificially disturbed depressurization production is likely to cause the collapse of inclined reservoirs and trigger large-scale hydrate decomposition. Hydrate decomposition leads to a decrease in sediment cohesion, which puts the slope at risk of destabilization, and the most dangerous area covers the hydrate decomposition zone. The placement of production well at the bottom of subsea slopes to increase production efficiency may affect reservoir stability. From the numerical simulation study of seafloor geological risk issues, the theoretical model of multi-field coupling can be used to describe and evaluate the seafloor geological risk issues during depressurization production. The theoretical model needs to be established from the perspective of multi-field coupling, and the controlling equations that accurately describe the characteristics of the reservoir are the key theoretical basis for evaluating the stability of seafloor geomechanics.

In order to reveal the landslide mechanism of hydrate formation, geophysical field observation techniques are indispensable. Acoustic waves can propagate within the hydrate formation and be reflected, refracted, or absorbed by different strata, and acoustic wave monitoring technology is an important means to assess the production of marine gas hydrate reservoirs. Gas production in natural gas hydrate reservoirs involves an in situ phase transition of solid hydrate decomposition, and the use of non-contact observation means of acoustic wave propagation speed, reflection characteristics, and other information that can be inferred via in situ hydrate decomposition and stratum deformation. Resistivity sensors are buried in the reservoir to obtain the temperature and pressure characteristics of the reservoir and the in situ hydrate decomposition information in real time, so as to strengthen the ability to recognize the hydrate generation and decomposition process in the formation. Moreover, resistivity imaging technology is utilized to measure the spatial distribution of underground resistivity in order to obtain three-dimensional imaging of the formation structure and the hydrate distribution in real time, thus inferring the stability of formation slopes. In addition, natural gas hydrate formation landslides are often accompanied by changes in formation vibration signals, and monitoring the vibration of the formation can provide landslide precursor information to predict the landslide risk that may be triggered by formation deformation. The comprehensive use of acoustic, electrical, vibration and other geophysical data, as well as the development of multi-parameter cross-analysis technical means, can more comprehensively and finely characterize the deformation and slippage of natural gas hydrate formations.

Reservoir deformation and super porous pressure usually occur inside the hydrate formation, and the limitations of the submarine environment restrict the traditional monitoring means, and there is an urgent need to develop monitoring equipment and techniques applicable to the submarine environment and the complex hydrate formation structure. The research and development of the submarine landslide field monitoring system faces many technical difficulties. Hydrate reservoir deformation is usually a slow and gradual process, and the monitoring accuracy is required to be high. The displacement generated by submarine landslides is large, and although the existing monitoring technology can realize accurate monitoring of small centimeter-level deformation, it is difficult to improve its monitoring range. Therefore, it is necessary to develop high-precision, large-range, and long-term stable monitoring means to sense the deformation signals of the hydrate reservoir and its overburden in real time. For on-site inspection, real-time monitoring devices such as turbidity meters, pore pressure sensors, resistivity probes, methane leak detectors and acoustic measurements need to be deployed at points on the surface of the overburden, and displacement monitoring devices need to be deployed in the overburden and the interior of the hydrate reservoir, to form a full-profile, refined real-time inspection system.

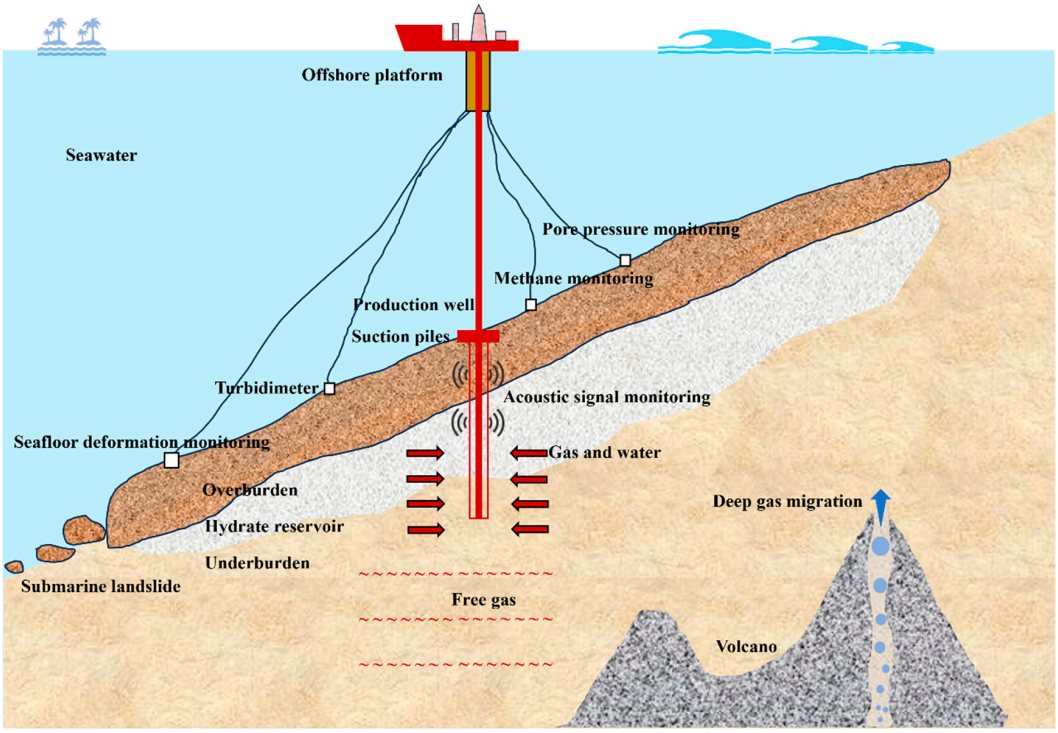


Figure 8. Natural factors and anthropogenic disturbances inducing a submarine landslide (cited from Yan et al., 2020; Vanneste et al., 2014) [2,106].

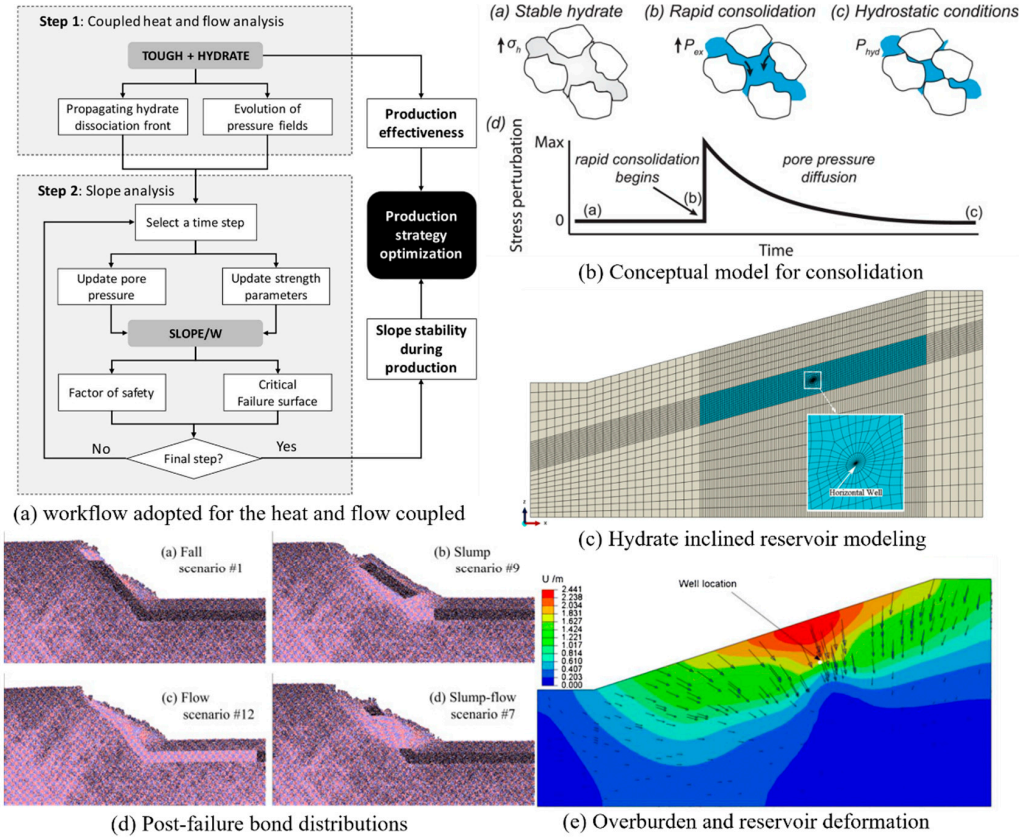


Figure 9. Numerical simulation study of the submarine landslide risk issues in hydrate formations (cited from Tan et al., 2021; Jiang et al., 2015; Handwerger et al., 2017; Song et al., 2019) [111–114].

Table 6. Hydrate depressurization production scheme and seafloor slope stability evaluation methodology.

Main Theoretical Model	Slope Stability Analysis Methods	Production Method	Mechanism of Slope Destabilization in Hydrate Formations	Inclination Angle	Reference
Multi-field coupled modeling of transient pore pressure due to hydrate decomposition	Limit equilibrium slope analysis method	Warming waters at the bottom of the slope trigger hydrate decomposition	Gas migration to overburden to form super pore pressure	3°, 20°	Liu et al. [110]
Modeling the dynamics of pore pressure and slope strength parameters during the production process	Limit equilibrium slope analysis method	Huff–puff method through a horizontal well	Strength loss due to super pore pressure formation and hydrate decomposition	10°	Tan et al. [111]
Coupling computational fluid dynamics and CFD-DEM model	Characterization of microfracture evolution	Instantaneous thermal dissociation of a methane hydrate	Dissipation of elastic strain energy in a short period of time driven by super pore pressure after hydrate decomposition	45°	Jiang et al. [112]
Ontological relationships for changes in sediment strength before and after hydrate decomposition	Rate and state friction model	Anomalous destabilization of hydrate	The presence of hydrates can significantly affect sediment strength increasing slope stability	5°~10°	Handwerger et al. [113]
Multi-field coupled model considering nonlinear theory and Moore–Cullen criterion	Orthogonal experimental design and the strength reduction method	Depressurization through a horizontal well	Both the extent of hydrate decomposition and the thickness of the overburden affect slope stability	15°	Song et al. [114]

3. Submarine Geological Risk Trigger Secondary Disaster

3.1. Gas Eruption

The factors inducing the generation of gas eruptions can be classified as natural geological activities and hydrate extraction disturbances. According to the scale of gas eruption, it can be classified into slow fluid migration caused by stratigraphic fractures and violent gas release caused by superporous pressure. Geological activity at depth causes natural gas to be transported upward and accumulate in the pores of this confined space, where gas hydrates are formed at low temperatures as the deposition process continues and pore pressure increases. However, geological activities such as earthquakes can create fissures in the strata that break up the confined space and create channels to the seafloor surface, leading to a sudden release of pore pressure and hydrate decomposition. Observational studies at the seafloor site in the Black Sea have shown that hydrate can decompose in situ into natural gas and rise to sea level in the form of gas bubbles [115], as shown in Figure 10. It is hypothesized that the behavior of gas hydrate decomposition in the Black Sea is due to natural factors, as geologic activity on the seafloor has created fractures in the reservoir buried beneath the overburden that are connected to the seafloor surface. Under the action of the natural environment, high-temperature fluid from geological activities such as volcanic eruptions increase hydrate reservoir temperature, leading to hydrate decomposition. Deep warm fluid has an obvious promoting effect on hydrate decomposition, changing the temperature and pressure conditions of the formation and affecting the internal structure of the formation, leading to the instability of the hydrate formation. Gas and water released from hydrate decomposition will gather and cannot be discharged from the formation in time, resulting in super pore pressure, and the pressure will gather to a certain extent, causing the formation to have fissure channels and resulting in gas eruption. Submarine earthquakes and volcanic activity can damage hydrate reservoirs and create fissures that connect to the seafloor surface. Natural gas is always less dense than seawater, and when there is a dense concentration of bubbles on the seafloor, the bubbles rise to form a plume. As the bubble plume rises, the bubble volume expands due to the decrease in pressure. Under the effect of buoyancy, the natural gas is eventually released into the

atmosphere [116–119]. Natural gas hydrates endowed on the seafloor are dominated by methane hydrate, a greenhouse effect gas that has 21–25 times the ability to influence global temperatures than carbon dioxide of the same mass [120,121]. If the methane gas stored in the seabed strata is released, it will cause incalculable harm to the global environment.

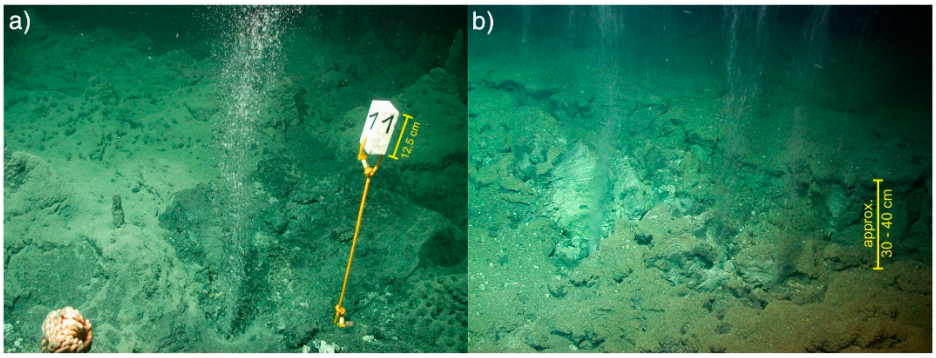


Figure 10. Natural gas leakage due to in situ decomposition of submarine hydrate (cited from Pape et al., 2011) [115]. (**a**) Free gas bubble escape from seafloor (**b**) Gas bubbles escape from diverse orifices.

The disturbance of depressurization production causes gas hydrate decomposition in the reservoir to produce gas, due to the low permeability of hydrate-bearing reservoir, and the permeability of the overburden layer is lower than the permeability of the reservoir, so that the gas cannot be discharged in a timely manner and is easy to produce super pore pressure in the formation. When a combined depressurization and reservoir heating method is used, the high-temperature environment promotes large scale decomposition in the hydrate reservoir. Heating causes heat to move faster through the reservoir, while low permeability causes low pore pressure to move slowly through the reservoir. Low permeability hydrate-bearing sediment is present between the hydrate decomposition region and the low pore pressure region. This prevents the gas from flowing to the production well in a timely manner and tends to cause the gas to accumulate inside the reservoir, which in turn leads to the formation of super pore pressure. Sand production risk clogging wellbores or transport pipelines, and wellbore instability risk during depressurization production damaging production well, undoubtedly impede the normal extraction of natural gas from the reservoir and increase the risk of gas build-up in the reservoir. Sand production and wellbore instability during depressurization production affects gas production and prevents gas from escaping in time, leading to the formation of excess pore pressures. When the pore pressure reaches a limit that the overburden cannot withstand, fracture channels will be generated, causing sudden gas release and violent gas eruption [122,123].

Studying the slope instability of hydrate formation triggered by super porous pressure associated with gas hydrate development is of great significance in exploring the mechanism of formation instability triggered by gas eruptions. In an experimental study, the gas eruption phenomenon is triggered by hydrate formation destabilization caused by super porous pressure, as shown in Figure 11. Liu et al. [124] established a visual observation device to simulate the slope damage process, which can apply high pressure gas to the low-permeability chalk layer sediment to simulate the super pore pressure generated by hydrate decomposition. At the same time, a data acquisition system was used to monitor the physical and morphological damage processes of overburden. The data acquisition system was also used to monitor the physical and morphological processes of overlying seafloor damage. Under the action of super pore pressure caused by hydrate decomposition, the typical phenomena of overlying seafloor damage are pockmark deformation and shear damage. Zhang et al. [125] established a centrifugal simulation experiment system for seafloor landslides, and a high-pressure fluid can be passed into the slope device to simulate the super pore pressure phenomenon caused by gas hydrate decomposition. The test equipment helps to study the tensile damage behavior of hydrate formation slopes in-

duced by super pore pressure and the formation shear instability caused by the dissipation of pore pressure due to crack formation during the downward movement of steep slopes. Climate warming and seafloor temperature rise have a relatively slow effect on hydrate decomposition, while the temperature at the bottom of the reservoir rises rapidly when the thermal stimulation method is used to extract hydrates. Song et al. [126] established a test system to simulate the effect of deep fluid migration on the stability of seafloor slopes. With the accumulation of gas in the device, the overburden of the hydrate reservoir deforms continuously, forming a dome on the seafloor, and the increase of super pore pressure will trigger the formation of hydraulic fractures at the edge of the dome, so that the gas is ejected from the seafloor to cause gas eruptions at the seafloor hydrate system landslides. In addition to indoor experimental studies, Sun et al. [127] established complex deep-sea engineering geologic in situ monitoring equipment for hydrate reservoir landslide monitoring and early warning technology, which utilizes seafloor three-dimensional electrical and acoustic measurements for in situ monitoring in order to obtain the parameters of sediment engineering properties. Sediment index parameters such as grain size, bulk weight, water content, porosity, and other sediment index parameters can be obtained through in situ long-term observation of spatial and temporal variations in seafloor sediment resistivity, acoustic velocity, and acoustic attenuation, and geophysical intrusion analysis [128]. Field monitoring data combined with indoor physical and mechanical characterization tests to establish the relationship between seafloor resistivity, acoustic parameters, and soil deformation strength indicators can be used to quantitatively describe the dynamic process of the hydrate decomposition-induced seafloor stratigraphic gas eruption disaster.

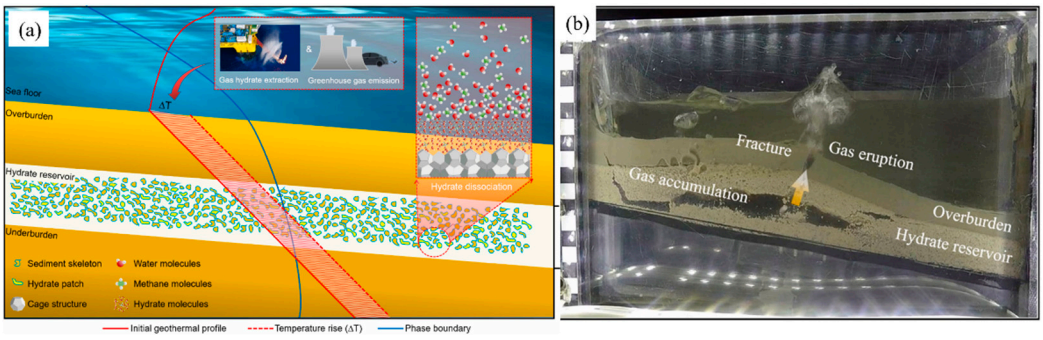


Figure 11. Gas eruption triggered by super pore pressure (cited from Song et al., 2023) [126]. (**a**) Effects of warming on hydrate reservoir (**b**) Gas eruptions cause slope damage.

3.2. Seawater Intrusion

Depressurization production releases natural gas from the reservoir and creates low pressure zones in the formation centered on the wellbore, with low pressure propagation expanding as extraction time increases. Under the influence of depressurization, osmotic pressure is generated between low pressure zones inside the reservoir and the seafloor–seawater boundary layer, which encourages seawater to flow through the low permeability overburden to the reservoir. The depressurization induces hydrate decomposition around the wellbore, and unlike overburden and hydrate-bearing sediments, the wellbore generally has higher permeability around the wellbore after hydrate decomposition. The pore pressure around the wellbore is the center of low pressure on the seafloor, and the strength of the sediments has been severely weakened after hydrate decomposition. In particular, the seafloor around the wellbore has a higher risk of overburden instability. Damage from overburden destabilization can easily form a connection between the reservoir and the seafloor, enhancing the permeability of the overburden and triggering an influx of seawater into the reservoir under osmotic pressure. If the high pore pressure area is connected to the seafloor, gas eruption will be formed; if low pressure area is connected to the seafloor, seawater intrusion will be formed, and the seawater intrusion schematic diagram is shown in Figure 12.

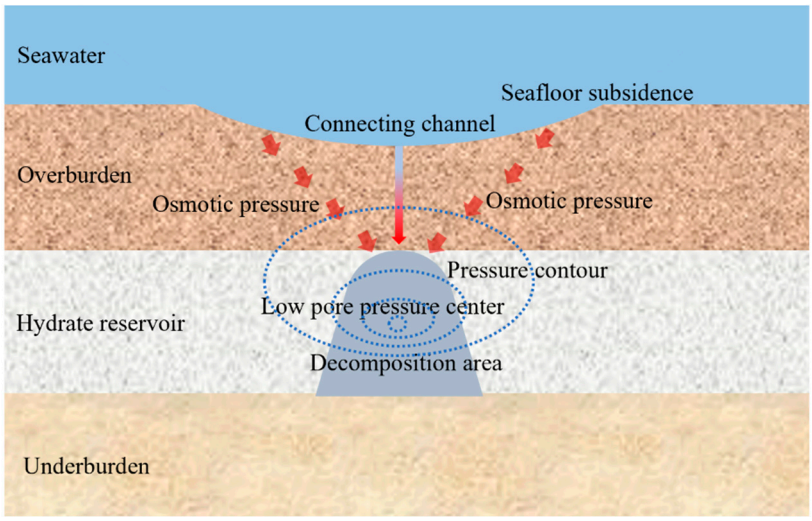


Figure 12. Schematic of seafloor subsidence caused by horizontal well depressurization production leading to seawater intrusion.

The entry of seawater into the reservoir changes the physical properties of the reservoir, increasing the water content of the reservoir and increasing the water production, which affects the extraction effect. From previous numerical simulation studies, it can be seen that the reservoir around the production wells may collapse due to stress concentration as mining continues. The hydrate decomposition range gradually increases, leading to large deformation in the overlying sediment layer. Uneven seafloor subsidence leads to destabilization or cracking in the overburden, and if the fracture connects the seafloor to the reservoir, then seawater intrusion will be triggered by osmotic pressure [102,104,129,130]. The destabilization or damage of the wellbore will also easily cause seawater to flow into the reservoir through the wellbore or the surrounding sediments under osmotic pressure, which will lead to seawater backflow. In order to effectively prevent wellbore instability, seafloor subsidence, and the risk of seawater backup, it is necessary to adopt mechanical property enhancement measures for the overburden layer above the wellbore. For example, grouting can be used to reinforce the overburden and reduce permeability at the same time.

3.3. Prospects

During depressurization production, there are potential submarine geological risks of sand production, wellbore instability, seafloor subsidence, and submarine landslides, and risk issues can cause secondary disasters dominated by gas eruptions and seawater intrusion. The current research on the risk of sand production includes field observation, numerical simulation and experimental research methods. Research on wellbore instability mainly adopts numerical simulation methods, and the research on seafloor subsidence and submarine landslides mainly adopts numerical simulation methods with experimental and a small amount of field observation research. There are fewer studies on secondary hazards, among which the experimental study of gas eruption lacks consideration of the disturbance of hydrate reservoir by depressurization production, and the study of seawater intrusion is basically in the blank. The field observation study of marine hydrate extraction is limited due to site and cost reasons. Experimental studies on the mechanical properties of hydrate-bearing sediment can help us to understand the evolution of the mechanical properties of the reservoir during depressurization production and reveal the mechanism of seafloor subsidence and submarine landslides. At present, numerical simulations and experimental studies are the mainstays of research on submarine geological risks and secondary disasters during depressurization production. Methods for studying the geological risks arising from submarine hydrate extraction cover a wide range of aspects, yet there is a gap between field and indoor studies, mainly due to the fact that indoor tests fail to adequately reproduce the in situ geological and engineering environments in the field. By

comprehensively utilizing a variety of research tools on the geological risk of gas hydrate, it is possible to gain a more comprehensive and in-depth understanding of the mechanism and characteristics of the submarine geological risk triggered by the perturbation of gas hydrate extraction, so as to provide a scientific basis for preventing and responding to the related geological hazards. A large-scale three-dimensional natural gas hydrate reservoir submarine geological risk test system should be developed to realistically reproduce the process of stratum instability and secondary geological hazards triggered by hydrate production disturbance in a high pressure and low temperature environment. Main influencing factors inducing the disasters should be sensed with the help of a full-profile and refined multi-physical quantity characterization system of the on-site geophysical observation, and the differences between indoor tests and the actual submarine environment can be overcome by combining these with numerical simulation to obtain an accurate and precise understanding. Combined with numerical simulation to overcome the differences between indoor experiments and the actual seabed environment, accurate and reliable experimental results can be obtained to improve the understanding of the mechanism of submarine geologic risk triggered by the disturbance of natural gas hydrate exploitation. The first and second production test projects of natural gas hydrates were carried out in the South China Sea in 2017 and 2020, and significant technological breakthroughs were achieved. Currently, the Ministry of Natural Resources is making every effort to push forward the preparatory work for the third hydrate production test project in the South China Sea. In future studies, the laboratory needs to build 3D, large-size equipment to simulate the real seafloor environment. Due to the complexity of hydrate decomposition and its multi-field coupling behavior, refined AI algorithms are needed for numerical calculations in future simulation studies.

4. Conclusions

Depressurization production of marine gas hydrates is prone to geological risks such as sand production, wellbore instability, seafloor subsidence, and seafloor landslides, as well as potential secondary hazards such as gas eruption and seawater intrusion. The research methods for submarine geological risk issues cover many aspects, including geophysical observation, indoor experimental research, and numerical simulation analysis. This paper reviews the progress of theoretical modeling and the potential geological risk problems during depressurization production on the basis of previous research on submarine engineering geological issues, and mainly obtains the following conclusions and outlooks:

(1) The threat level of potential geologic risk issues in hydrate formation destabilization can be classified into four aspects from shallow to deep: sand production, wellbore instability, seafloor subsidence, and submarine landslides. Geologic risk issues, in turn, cause secondary disasters dominated by natural gas eruptions and seawater intrusion. When assessing the geologic risks, theoretical modeling needs to be based on the perspective of multi-field coupling, in which the accurate description of reservoir permeability, temperature, geomechanics, and other control models are the key basis.

(2) Sand production is sensitive to production pressure and sediment mechanical properties, and excessive sand production seriously affects gas production. A large amount of sand production leads to the creation of holes in the reservoir and even affects overburden stability, which is not conducive to the maintenance of stratigraphic stability. If the development of holes is serious, it will damage the seafloor surface and lead to seawater intrusion into the reservoir.

(3) Hydrate decomposition reduces the mechanical strength of the sediment around the wellbore, causing it to reach a plastic yield state, and the plastic state of the sediment makes the wellbore susceptible to instability. Wellbore destabilization leads to gas leakage and environmental contamination and can also lead to seawater intrusion due to the connection between the seabed surface and the reservoir.

(4) The gas and water released from the hydrate decomposition are aggregated and cannot be discharged in time to generate super pore pressure, and the pressure is aggregated to a certain level to cause gas eruption through the fracture channels in the formation under the effects of overburden failure. The pore pressure around the wellbore is a low-pressure center on the seabed that triggers seawater influx into the reservoir under the promotion of osmotic pressure.
(5) Hydrate decomposition weakens the mechanical strength of the reservoir and may generate super porous pressure, inducing a submarine landslide or a gas eruption. Hydrate reservoirs need to be filled with gravel to enhance their mechanical strength and permeability, and overburden needs to be grouted to reinforce stability. The study of submarine geological risk and its secondary disasters requires the cross-application of various research tools.

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