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A Review of Potential Geological Hazards and Precautions in the Mining of Submarine Natural Gas Hydrate

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Abstract: Natural gas hydrate (NGH hereafter), commonly known as combustible ice ($(CH_4)n{\cdot}mH_2O$), is an abundant non-conventional clean energy resource. It is mainly located in permafrost areas and submarine sediment layers at depths of 0–200 m and 300~3000 m underwater. Submarine NGH accounts for about 97%. Its commercial mining may be a solution to mankind's future energy problems, as well as the beginning of a series of geological risks. These risks can be divided into two categories: natural geological hazards and secondary geological accidents. Based on the viewpoints of Earth system science researchers, this paper discusses the main potential geo-hazards of submarine NGH mining: stratum subsidence, seafloor landslides, the greenhouse effect, sand piping, well blowout, and wellbore instability. To minimize the potential catastrophic impacts on the Earth's ecosystem or mechanical accidents, corresponding technical precautions and policy suggestions have been put forward. Hopefully, this paper will provide a useful reference for the commercial mining of NGH.

Keywords: NGH; geological risks; precautionary measures; commercial mining

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1. Introduction

The massive use of fossil fuels is unsustainable and may have serious negative consequences. One example is climate change, which is becoming an increasingly significant concern for the international community. Petroleum consumption ascended to more than 97 million barrels per day in 2023. However, the proven global petroleum reserves left are about 1.7 trillion barrels, roughly enough for only 50 years [1]. In addition, the Russia–Ukraine conflict has profoundly affected the traditional energy supply chain. What is the future of human energy? The discovery of NGH has opened up a new solution to energy problems. NGH, commonly known as combustible ice ($(CH_4)n{\cdot}mH_2O$), is a crystalline solid compound formed by water molecules and methane molecules (with methane accounting for the majority) [2]. Widely located in submarine sediments and permafrost zones under conditions of low temperature and high pressure, it burns with a very small amount of carbon emission when it meets fire. NGH is mainly located in permafrost areas and within the top 0–200 m of submarine sediment layers at water depths of 300~3000 m. Submarine NGH accounts for about 97%. Its global reserves are estimated to be as high as 1.5×10^{15} m^3, twice the reserves of traditional fossil energy sources [3–5]. It is anticipated to be a feasible

substitute for traditional fossil fuels, marking a shift to a sustainable-energy-dominated stage because of its cleanliness and large reserves [6–9]. Submarine NGH is mainly located in the 0–200 m sediment layer of the seabed surface, the so-called NGH Stability Zone (NGHSZ), where methane molecules are firmly fixed in the center of a cagelike structure in the stable form of NGH [10,11]. However, once the NGHSZ is destroyed due to submarine drilling, NGH will decompose into methane gas and water, and the volume will rapidly expand (1 unit of NGH dissociation can release about 160 times as much gas in the standard state) [12]. This phase transition will significantly reduce the bonding strength and shear strength of submarine sediments. Various geological hazards, such as stratum subsidence, seafloor landslides, the greenhouse effect, sand piping, well blowout, and wellbore instability, may be induced.

Depressurization [13,14], thermal stimulation [15], and inhibitor injection [16,17] are three mainstream technologies for gas production from submarine hydrate-bearing sediments. Most scholars believe that the commercial mining of NGH will have catastrophic impacts on the ocean ecosystem and pose potential threats to the subsequent production operation as depressurization or heating during mining will significantly change the NGH occurrence environment, characterized by low temperature and high pressure [18–24]. Submarine sediments generally exhibit poor cementation and diagenesis [11,25,26]. The long-term extraction of pore NGH will inevitably result in NGH-bearing sediments, and the overlying sediments will be subjected to deformation and subsidence of varying degrees [27–30]. He et al. [31] revealed that hydrate decomposition exacerbates the risk of wellbore instability, which will lead to more geological hazards, through the construction of coupled models. Zhang et al. [32] investigated the wellbore destabilization problem caused by deep-well exploitation and emphasized that deep-well exploitation may lead to chain reactions, such as seafloor landslides, stratum subsidence, and wellbore safety hazards. Li et al. [19] explored sediment deformation using the ABAQUS platform, showing that sediment instability around the wellbore occurs mainly in the early operation stage, which can lead to sand production. However, sediment instability near the seabed occurs in the late operation stage, which may lead to submarine landslides. Luo et al. [33] analyzed the deformation behavior of submarine sediments when depressurization and thermal stimulation techniques were applied to gas production. Song et al. [20] elaborated on the features and patterns of subsubmarine landslides induced by gas extraction from the seafloor. Wan et al. [27] analyzed the reservoir deformation associated with vertical wellbores. Wang et al. [34] experimentally studied the effect of hydrate dissociation on sediment deformation. Zhang et al. [35] revealed that the stability of hydrate reservoirs is worst in the direction of the minimum horizontal principal stress. Zhou et al. [36] investigated the mechanical responses of five selected elements at different locations in the hydrate gas production region, showing that the mechanical responses of hydrate-bearing sediments at specific locations are related to their hydrate dissociation status, which can be typically divided into the before, during, and after stages of hydrate dissociation. These studies collectively show that changes in the physical and mechanical properties of the strata triggered by mining activities can significantly affect the stability of the seabed geological structure through the interaction of multiple factors, and that the optimization of the mining process is required to control risk in engineering design.

Many countries have carried out NGH depressurization production testing (Table 1) [19,37–46]. It is high time we discussed the potential geological hazards and risk precautions for the NGH trial mining stage. In order to minimize potential risks, this paper will identify the potential geological hazards in submarine NGH mining and put forward corresponding precautions and warnings based on the theory of Earth system science.

Table 1. Summary of NGH mining by decompression methods.

NGH Mining Area	Time	Reservoir Characterization	Mode of Mining	The Total Gas Output of NGH
Nankai, Japan	March 2013	Water depth: 1000 m Burial depth: 300–360 m Type: Sand layer Average initial permeability: 20 mD	Depressurization production	Cumulative: 11.9×10^4 m^3 Average: 2.0×10^4 m^3/d
Nankai, Japan	May 2017	Water depth: 1000 m Burial depth: 300–360 m Type: Sand layer Average initial permeability: 20 mD	Depressurization production	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	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	Cumulative: 8614×10^4 m^3 Average: 2.87×10^4 m^3/d
Alaska, USA	May 2012	-	CO_2 displacement production	Cumulative: 30×10^4 m^3

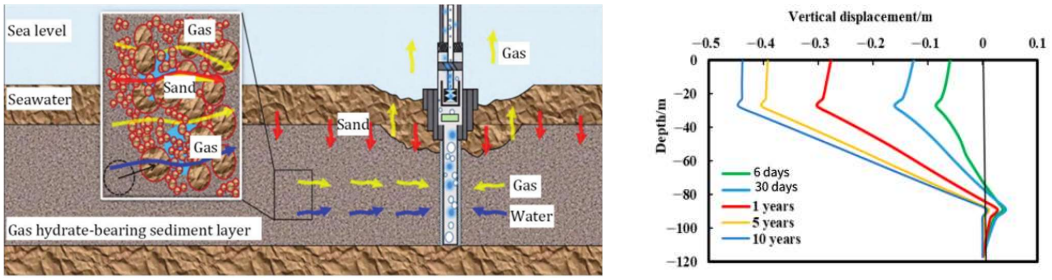
2. Potential Geological Hazards in NGH Mining

In this paper, the potential geological hazards in NGH mining are divided into two main categories: natural geological hazards and secondary geological accidents. The former includes stratum subsidence, seafloor landslides, and the greenhouse effect; the latter includes sand piping, well blowout, and wellbore instability.

2.1. Stratum Subsidence

Stratum subsidence refers to the stratum vertical displacement resulting from crustal movement, industrial mining, or other factors. NGH mining will induce the decline of submarine strata. The faster the hydrate dissociation speed, the greater the stratum subsidence rate [47]. When NGH is extracted by drilling tools, hydrate dissociation is accelerated, stratum porosity is increased, and excessive pore pressure is generated [32]. The original shearing strength and mechanical equilibrium system of the seafloor are disrupted, which leads to vertical displacement of the sedimentary layer, and ultimately results in stratum subsidence (Figure 1a).

Li et al. [48] conducted a ten-year simulation experiment on gas hydrate extraction to deeply analyze the dynamic stratum subsidence. The experiment revealed the functional relationship between vertical displacement and well depth over the production times of 6 days, 30 days, 1 year, 5 years, and 10 years. The results show that the stratigraphic subsidence is particularly significant around the upper part of the wellbore, and the subsidence tendency becomes worse with time. However, the rate of subsidence slows significantly after 1 year of mining. Notably, a slight stratum uplift was observed near the lower part of the wellbore, which peaked at 4.2 cm at 30 days (Figure 1b). The study highlights that long-term mining-induced stratum subsidence may cause serious damage to offshore drilling facilities, and marine biological environments.



(**a**) (**b**)

Figure 1. Stratum subsidence due to NGH drilling (modified from reference [48,49]). (**a**) Diagram of NGH migration and stratum change. (**b**) Functional relationship between vertical displacement and borehole depth (reproduced with permission from [48]; [*Energy & Fuels*]; published by the American Chemical Society [2021]).

2.2. Seafloor Landslide

A seafloor landslide is a phenomenon where the seabed sediments collapse to form a flowing body under the influence of such natural factors as earthquakes or human factors, and the body moves along the deep sea under the force of gravity. According to the forms of sediment collapse, they can be classified as block landslides, fluvial landslides, or shallow slab landslides. According to the movement modes, they include creeping, sliding, turbidity flows, block flows, and debris avalanches. Five typical seafloor landslides have been recorded. Studies show that there is a strong coupling relationship between submarine landslides and hydrate decomposition in the South China Sea [50]. Ma et al. [51] have pointed out that seafloor landslides occurring during NGH exploitation pose a fatal threat to marine ecology and human safety. In addition, if the large amount of gas produced by hydrate decomposition is not properly released in time, the ultra-high pore pressure will further deteriorate the stability of seafloor slopes [52,53].

Both natural environmental factors and human factors can result in seafloor landslides in NGH-bearing sediment strata [54,55]. The natural environmental factors mainly include the NGH dissociation caused by global warming, and the human factors are mainly the temperature and pressure changes of the hydrate reservoir caused by NGH mining. No matter what factors they are, it all comes down to the basic incentive cause: submarine NGH dissociation. Hydrate extraction leads to the instability of the lower boundary of NGH, further movement of large block of sediments under the force of gravity currents, and seafloor landslides happen (Figure 2). With the advancement of the commercial mining of NGH in the future, the possibility of triggering seafloor landslide will increase. Seafloor landslides will impair the operation of seafloor monitoring tools and drilling equipment.

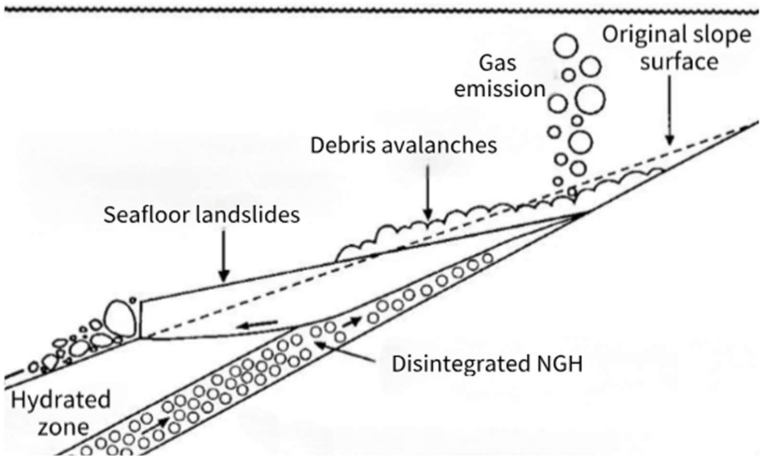


Figure 2. Seafloor landslides resulting from NGH extraction (modified from reference [56]).

2.3. Greenhouse Effect

The greenhouse effect will lead to significant climate change and extreme natural disasters, such as tsunamis, droughts, and floods, a growing global concern for international communities. On the one hand, in situ emission of natural gas was observed at the seafloor of the Black Sea [57]. On the other hand, geological hazards such as submarine earthquakes or volcanoes can create fractures or faults on the seafloor surface, resulting in a sudden and plentiful release of pore pressure gas. In addition, submarine NGH extraction will emit more greenhouse gases and eventually intensify the greenhouse effect. The marine temperature simulation in the Sea of Okhotsk in 2014, the Gulf Stream, and the Gulf of Mexico showed a 1–2 °C increase in 100 years due to submarine NGH extraction (Figure 3).

Methane-derived carbon is absorbed by Planktonic Foraminifera, Benthic Foraminifera, and carbonate rocks after methane seepage. This process is reflected in the following two chemical equations: $CH_4 + O_2 \rightarrow H_2O + CO_2$ (1); and $CH_4 + SO_4^{2-} \rightarrow HS^- + HCO_3^-$ (2). The carbon values can be measured by δ13C in the biomarkers and carbonate rocks. During geological history, NGH emission resulted in the end of the 'snowball' Earth during the Neoproterozoic era and a temperature increase of 6–12 °C in the Northern Hemisphere during the Paleocene–Eocene [58,59]. Methane is more harmful in terms of global warming than carbon emissions in industry. IPCC (UN Intergovernmental Panel on Climate Change) studies show that the greenhouse effect derived from CH_4 is 82.5 times as high as that from CO_2 on a 20-year time scale, and 29.8 times as high on a 100-year time scale [60].

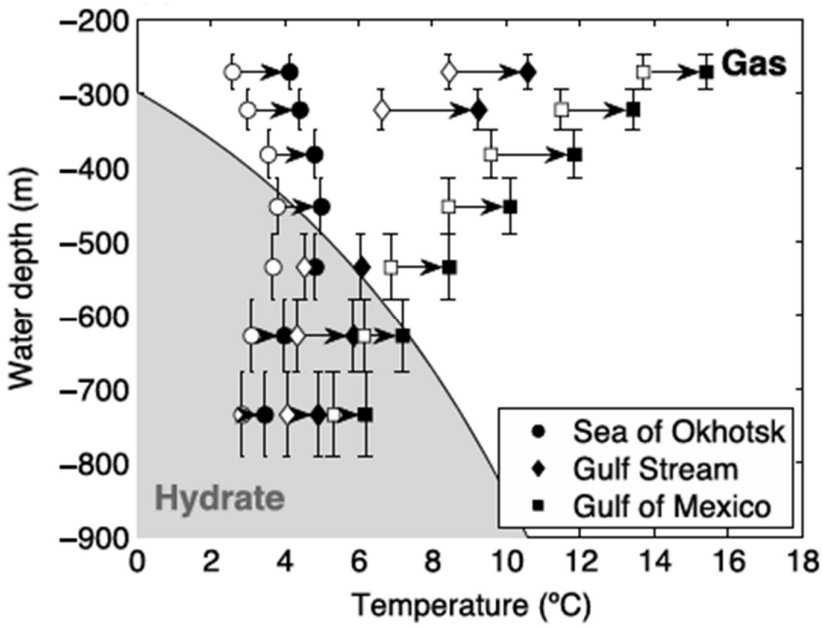


Figure 3. Marine temperature simulation showing a 1–2 °C increase (modified from reference [61]).

2.4. Sand Piping

Sand piping refers to the phenomenon where sand surges into the wellbore due to the pressure difference between the inside and the outside in the petroleum and gas drilling process, resulting in the blockage of the transportation passage. When the NGH dissociation (D_H) rate increases from 30% to 60%, the plastic strain increases from 2.3% to 2.8%. The probability is that sand piping will happen (Figure 4).

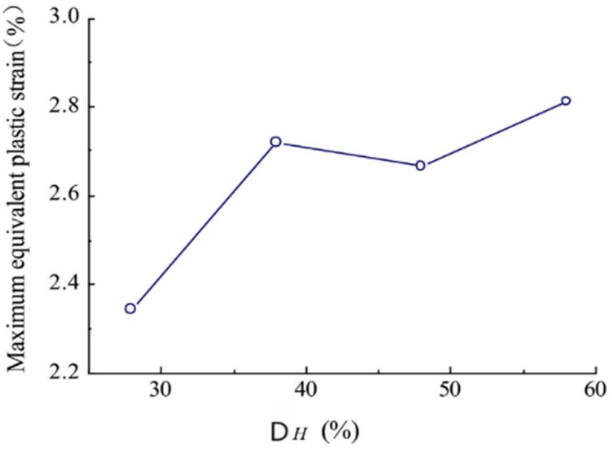


Figure 4. The relationship between NGH solubility and plastic strain ([62], reproduced with permission from [Yan, C. et al.]; [*Journal of natural gas science and engineering*]; published by ScienceDirect [2018]).

The commonly adopted depressurization method is more likely to result in a large amount of sand entering the wellbore and forming a blockage in mining. Excessive sand piping can cause serious damage to drilling tools, instability, and blockage of the wellbore. A typical example was when Japan failed in submarine NGH extraction due to sand piping.

2.5. Well Blowout

A well blowout is a phenomenon where petroleum, gas, or water suddenly erupts in an uncontrolled state due to pressure inconsistencies between the inside of the well and the outside. In offshore drilling operations, blowout accidents are extremely serious hazards, directly threatening physical safety, the marine environment, and economic benefits. In 2003, a well blowout occurred in Chongqing, with the tragic consequence of 243 deaths. NGH extraction also has the potential risk of well blowouts. When the pressure outside the well wall is too strong, excessive hydrate will surge into the well, which may lead to a blowout. Pipeline blocks, gas leakage, and even explosions may be induced when there is insufficient space inside the well (Figure 5).

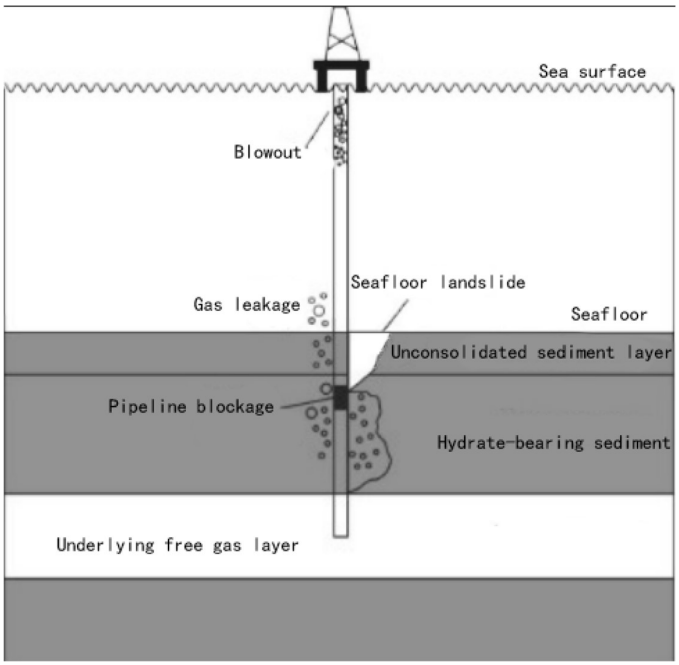


Figure 5. Principle of well blowout in NGH extraction (modified from reference [63]).

Regarding well blowouts formed during the NGH extraction process, scholars have mainly conducted research in three major forms: case study research, risk model construction, and experimental process simulation. Chen et al. [64] constructed a Bayesian network mode, specifically applied to offshore drilling operations, and simulated the blowout accident in the South China Sea. Johansen [65] conducted research on deep-water blowout cases and compared the research results with shallow-water blowout cases. Clarkson's deep-water oil and gas model simulated 30 blowout scenarios based on many actual cases. The simulation clearly showed significant differences in the prevalence of blowout plumes under different environmental conditions and different types of gases [66]. Sun et al. [67] simulated seven types of well blowouts by building a multinomial flow model and classified the blowouts into three phases: development of well kick, development of blowout, and a borehole stage with little mud.

2.6. Wellbore Instability

Wellbore instability is primarily a function of how submarine strata respond to the induced stress focused around the wellbore during various drilling activities. Many models have been developed for instability analysis and much progress has been made so far. However, wellbore instability continues to pose a considerable threat to successful well operations. A case in point is the rig explosion in the Gulf of Mexico on 20 April 2010, which was directly attributed to wellbore stability failure. The accident resulted in the deaths of 11 operators, serious contamination of more than 2000 km^2 of sea area, and great damage to the marine ecosystem. This incident highlights the disastrous consequences of wellbore instability in practical engineering under complex geological conditions.

Quantitative risk evaluations of the wellbore instability in high-temperature and high-pressure wells have been carried out by scholars [68–71]. More details related to wellbore instability are shown in Table 2 below [72,73].

Table 2. Types, conditions, examples, causes, and symptoms of wellbore instability.

Type	Occurrence Conditions	Typical Examples	Causes	Instability Symptoms
Tensile failure (stress failure)	When the strain created by borehole pressure exceeds the internal stress of the rock formation	Wellbore fracturing, hole enlargement	(1) Physical causes: tectonically stressed formations, anomalously high in situ stresses, naturally over-pressured collapse, naturally fractured or faulted formations (2) Man-made factors: drilling fluid density, well inclination, temporary wellbore pressures, drill string vibrations, drilling fluid temperature, induced over-pressured seafloor collapse, poor hole cleaning (3) Rock–fluid interaction	(1) Direct: oversized hole, undergauged hole, excessive volume of cuttings, excessive volume of cavings, cavings at the surface, hole fill after tripping, excess cement volume required, deviation control problems. (2) Indirect: high torque and drag, hanging up of drill string, casing, or coiled tubing, increased circulating pressures, stuck pipe, excessive drill string vibrations, drill string failure, inability to run logs, poor logging response, annular gas leakage due to poor cement job, keyhole seating, excessive doglegs
Shear failure	When the strain created by borehole pressure is less than the internal stress of the rock formation	Wellbore collapse, tight holes		

Maximizing the prevention of potential geological hazards is a crucial step in the future commercial mining of submarine NGH.

3. Technical Precautions

Previous studies [74–77] have provided the theoretical basis for the prevention and control of geological hazards in NGH extraction. This paper proposes the following technical precautions from the perspective of marine geological engineering.

3.1. Optimize the CO_2-EGR Method to Alleviate Stratum Subsidence

With the increase in gas production in NGH mining, the degree of stratum subsidence will increase. Our aim is to minimize the stratum subsidence (<0.05 m) while ensuring

the maximum outputs. Through numerical simulation, Xin et al. [78] revealed that the stratum subsidence caused by NGH depressurization mining mainly occurs in the early stages. Therefore, the depressurization range should be reduced in the early mining stage. Based on a coupled geomechanical model, Lin et al. [79] simulated the subsidence of seafloor strata during NGH drilling, showing that significant improvements in seafloor subsidence can be achieved with the optimization of carbon-dioxide-enhanced gas recovery (CO_2-EGR). Two cases of pure depressurization and CO_2 injection depressurization were simulated by experiments, showing that the subsidence is only 6.8% of pure decompression when the pressure drop is 30%, that is, the degree of stratum subsidence is significantly reduced when carbon dioxide is injected earlier. The mechanism is that the injection rate of CO_2 is subject to double constraints: One is that the maximum injection rate is limited to 3900 standard scm/day, and the other is limited by the maximum bottom hole pressure. When the CO_2 injection rate reached the maximum, it was found to be a stable injection parameter that keeps a balance between seafloor subsidence and NGH production. However, the technology is still in the experimental stage and has not yet been tested in the field, and more efforts need to be made in further research.

3.2. Fill Foamed Cement to Control Seafloor Landslides

For the seafloor landslides caused by NGH extraction, currently there are four slurry cementing operations. The most effective method is to apply a foaming machine, initially used in the field of making thermal insulation material, to drilling technology. The voids in the seafloor strata produced in NGH extraction can be quickly filled. A cable winch on the drilling platform is used to control the descending depth, filling the foamed cement slurry through the shot hole while a steering gear underneath is used to regulate the drilling depth (Figure 6). The study shows that filling foamed cement slurry at the same time as drilling can effectively support the stratum and greatly avoid the occurrence of seafloor landslides [80].

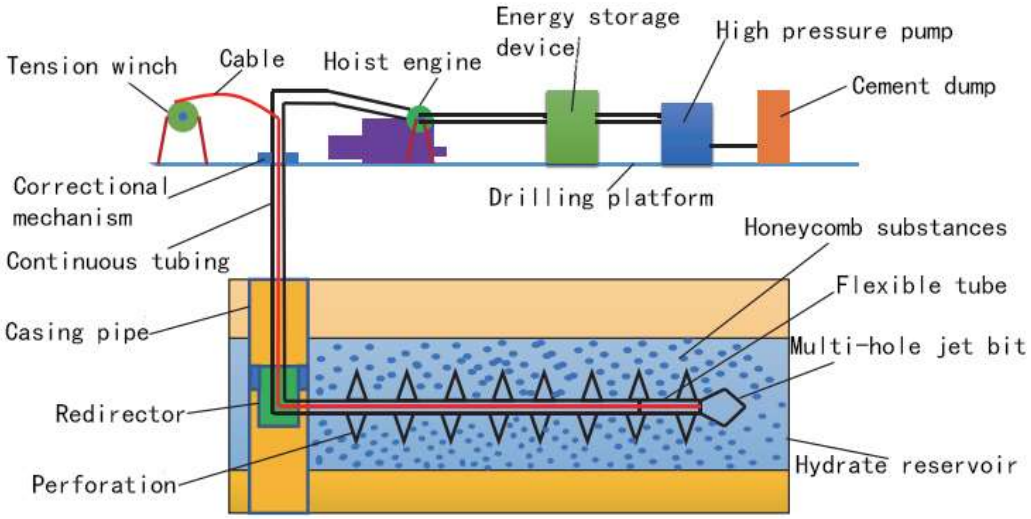


Figure 6. Principle of foaming machine in NGH drilling (modified from reference [80]).

3.3. Improve Drilling Technology to Mitigate the Greenhouse Effect

There are three main methods to slow down the emission of greenhouse gases: First, the use of petroleum-based or water-based drilling fluids bearing hydrate inhibitors can effectively depress the dissociation rate of NGH, ultimately slowing down the emission of greenhouse gases such as methane [81]. Second, the use of an emulsifier replacement can convert CH_4 produced in the dissociation of NGH into CO_2. As stated previously, CO_2 is a less harmful greenhouse gas than CH_4. Tian et al. [82] have shown that the CO_2

replacement method is a very efficient NGH mining method. When the recovery efficiency of CH_4 achieved by injecting the CO_2 mixture reaches about 6.95%, the storage rate of CO_2 is about 0.3. Third, biotechnology can absorb methane. Methanophilus, a kind of fungus which mainly feeds on methane, can be used to absorb the methane produced during hydrate dissociation. Our study shows that the second method will help promote a greener and cleaner gas hydrate extraction in the submarine environment.

3.4. Install a New Solid–Liquid Separator to Reduce Sand Piping

By installing an axial-flow annular in situ device, the target liquids are pumped out, leaving the unwanted solids on the seafloor during the mining process. There is no need for drilling tools to pump excessive sand-bearing material, reducing the sand piping (Figure 7).

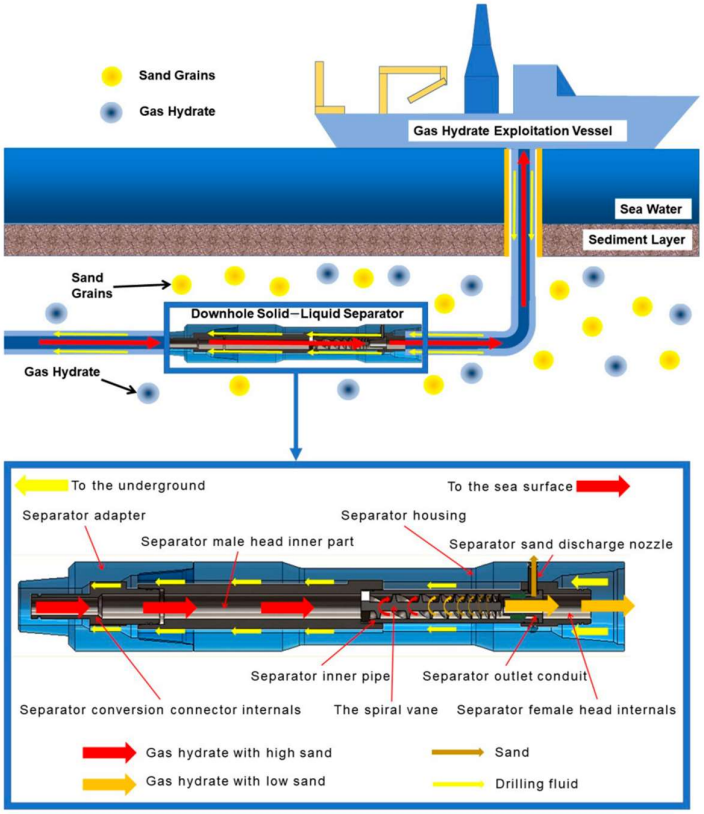


Figure 7. Principle of solid–liquid separator in NGH drilling ([83], reproduced with permission from Nie, Q. et al.; [*Energies*]; published by MDPI [2022]).

In addition, Figure 8 shows that sand production can be zero in theory if no pressure gradient is applied. However, this does not make any sense as there cannot be any gas production either. It is important to notice that the sand production is almost kept constant after gas production volumes of 1000 m^3. In other words, sand production is not affected by the rate of depressurization at the later stage. P8t2 has significantly lower sand production compared to the H5t2 stage. It is obvious that lowering the decompression rate is an effective operation strategy to reduce the early sand production stage.

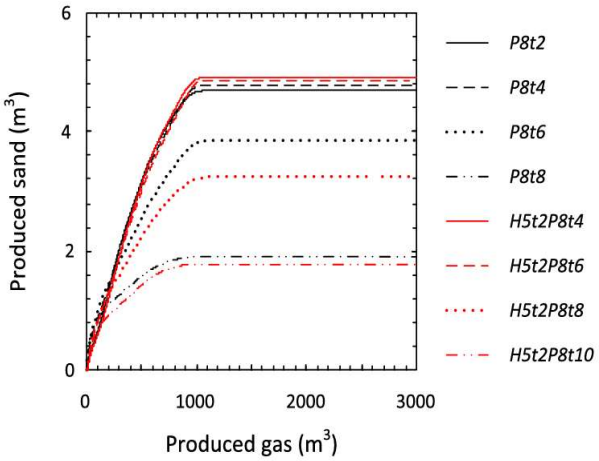


Figure 8. Sand production against gas production at different pressure gradients ([84], reproduced with permission from Uchida, S et al.; [*International Journal of Rock Mechanics and Mining Sciences*]; published by Science Direct [2016]).

3.5. Adopt New Inhibitor to Lower Well Blockage

At present, the issue of wellbore blockage is mainly alleviated by traditional inhibitors. Inhibitors can be divided into three main categories: thermodynamic inhibitors, mixed inhibitors, and kinetic hydrate inhibitors (Table 3) [85–97]. Yang et al. [89] have prepared a new low-dose polymer hydrate inhibitor HAY through monomers such as tetrahydrofuran and N-butenylpyrrolidone, which can more effectively inhibit hydrate formation and increase NGH production. Qin [90] found that the hydrate inhibition effects of self-made reagent PVP-BP are outstanding. The self-made reagent has no hydrate formation in the pipeline for up to 33 h at 8.4 K undercooling. When the temperature exceeds 8.4 K, hydrate formation is still less. Bu et al. [98] experimented on the effect of lecithin on mechanical properties at different concentrations, and confirmed that a 1.5% lecithin concentration in the cement slurry inhibits NGH decomposition. These studies provide a basis for optimizing the inhibitor formulation, suggesting that compounded inhibitors are more effective than single kinetic inhibitors.

Table 3. Types of, experiments on, and functions of NGH inhibitors.

Inhibitor Type	Experiment Method	Experimental Result	Inhibitor Mechanism	Inhibitor Effect
Thermodynamic inhibitors	1. Inhibitors containing a mixed salt solution of sodium chloride, potassium chloride, and NH4Cl, respectively	Sodium chloride is more effective	By adjusting the thermodynamic conditions of NGH, the gas production is inhibited	Strong stability; versatility; not limited by other mechanical conditions
	2. Different concentrations (1.5wt % and 3.0wt %) of sodium chloride solution on hydrate	Only under the condition of pure water is the sodium chloride solution effective		
	3. The hydrate formation rate under the concentration of ethylene glycol was 30.0 wt %	When the concentration of ethylene glycol is 30wt %, the hydrate inhibition effect is better		

Table 3. *Cont.*

Inhibitor Type	Experiment Method	Experimental Result	Inhibitor Mechanism	Inhibitor Effect
Mixed inhibitors	1. A mixed solution of sodium chloride and ethylene glycol	The result of mixed inhibitors is more effective than that of a single sodium chloride inhibitor	By using a mixed inhibitor of sodium chloride and ethylene glycol, the hydrate formation rate and wellbore blockage are slowed down	Strong inhibition effect; high economic type and adaptation to various environments
	2. The hydrate inhibition effect of MeOH and sodium chloride at different ratios	The effect of mixed inhibitors is better than the sum of single inhibitors		
	3. The common inhibitory effect of ethylene glycol and kinetic inhibitor	The mixing suppression effect is stronger		
	4. Hydrate inhibitor HAY	The mixed inhibitor of Tetrahydrofuran and N-butenyl pyrrolidone is more effective than a single inhibitor		
Kinetic hydrate inhibitor	1. The performance of different inhibitors was compared in a slow constant cooling experiment	Polymers containing dibutylamine groups are more potent inhibitors than polymers containing dimethylamine or diethylamine groups	It is economical and effective, environmentally friendly, and has little impact on the production process	The suppression effect is affected by many factors such as temperature and pressure, and there are differences between the laboratory evaluation method and the actual scene
	2. The effect of modified starch in inhibiting gas hydrates was studied	The results showed that, when the dosage of modified starch was 0.04wt %, the inhibition effect was the best		
	3. To study and compare the inhibitory effects of four kinds of amino acids, including aspartic acid, threonine, arginine, and valine, on NGH	Aspartic acid and threonine showed inhibitory effects, while the latter two amino acids played a promoting role		
	4. The effects of diethylene glycol butyl ether as a synergistic agent on four kinetic inhibitors, PVP, PVCap, VP/VC, and VC-713, were studied	Diethylene glycol butyl ether can significantly improve the efficiency of inhibitors		

3.6. Use a Low-Temperature Drilling Fluid to Keep Wellbore Stable

It is widely accepted that the temperature difference (ΔT) between drilling fluid and the stratum will trigger wellbore instability. Li et al. [99] have simulated the relationship between the status of NGH saturation, the variation of stratum mechanical properties, and wellbore stability (Figure 9). As the temperature of the drilling fluid gradually increases, the extent of the dissociated region of NGH around the borehole will expand. The results of the

study show that, when the temperature difference ΔT reaches 7 K, the deformation degree of the formation will reach the maximum value. Based on this, the use of low-temperature drilling fluid in the NGH extraction process helps to reduce the scope of NGH dissociation and improve the stability of the wellbore during the drilling process.

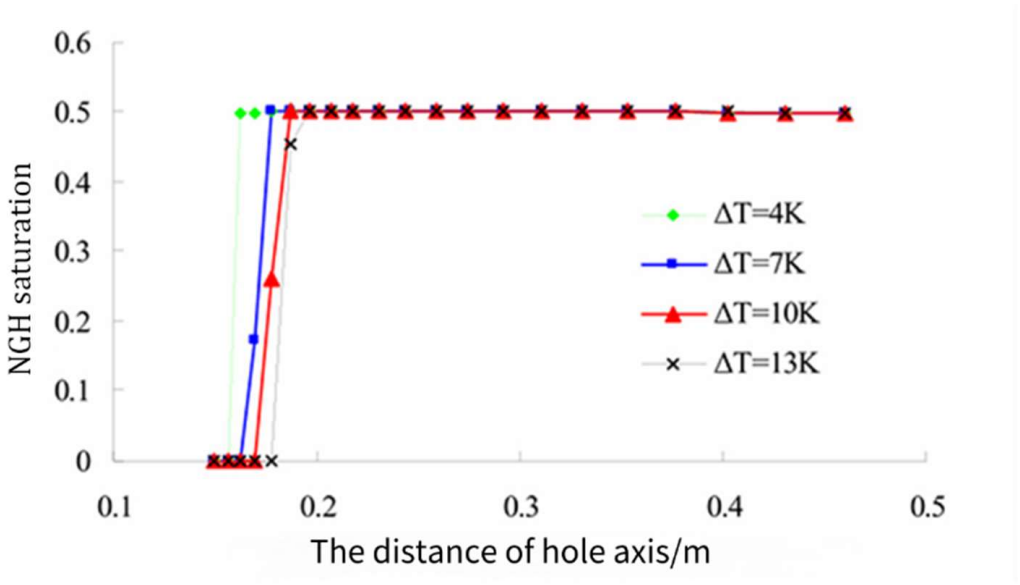


Figure 9. The distribution of hydrates saturation with ΔT ([99], reproduced with permission from Li, L et al.; [*Procedia Engineering*]; published by Science Direct [2011]).

4. Policy Suggestions

In addition to the above NGH drilling technology, the following policy suggestions are proposed to reduce the potential geological hazards.

4.1. Founding a Risk Identification Mechanism Through Marine Science and Technology Research

Marine science and technology are decisive factors in sustainable and low-risk submarine mineral resource development. Research pays much attention to advancement in two aspects: deep-sea drilling technology and deep-sea intelligent mining vehicles. Taking the latter as an example, laser radars are installed in front of intelligent mining vehicles to scan the seafloor surface, and sense rocks and other objects, and cameras are used to capture images for route planning and obstacle avoidance. At the same time, real-time positioning and map construction technology is applied to send its location and mapping information. Detailed data in the mining area can be provided for the deep-sea drilling equipment.

A risk intelligence analysis and decision-making system can effectively reduce the NGH mining risks (Figure 10). Firstly, the system supports weather forecasting and intelligent decision-making, as most of the international drilling accidents are caused by bad weather. Secondly, the system is a database of marine geology. Digital sensing technology is used to obtain raw data from NGH-bearing layers. Most importantly, the system is also a risk identification platform. It relies on big data to simulate the changes in the target area, predicts various types of geological hazards, judges the probability of potential risks, and takes appropriate measures.

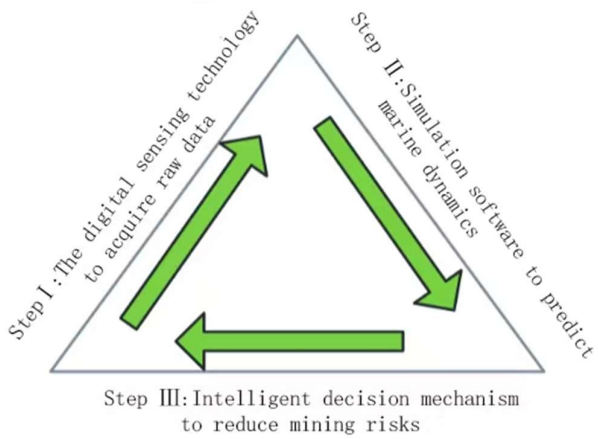


Figure 10. Intelligent risk identification and decision-making mechanism.

4.2. Establishing a Risk Warning Mechanism Through International Cooperation

Due to the breakthrough in submarine NGH mining technology, the cross-national feature of disasters, and the sensitivity of the mining sites, it is urgently required to establish an international cooperation platform. The type, scale, location, and duration of geological disasters are different. All countries should share their experiences in geological risk precautions.

Currently, international organizations believe that the heavy casualties and economic losses in the Southeast Asia tsunami in 2004 were closely related to the lack of an early warning system. An innovative early warning system has been proposed. The system includes a marine communication system, a marine early warning command office, a monitoring system for drilling tools, and appropriate back-up means, including a marine communication system, a marine early warning command office, and a monitoring system for drilling tools.

The designed mechanism (Figure 11) is centered on the marine early warning command office, connected with the submarine drilling platform by direct-line phones. Deep-sea early warning floats, seismic-with-drilling (SWD) tools, and other instruments are installed under the drilling tools to obtain seafloor stratum parameters, geological conditions, and other real-time data. According to the data, geological hazards will be accurately predicted, and corresponding measures will be taken. In the case of minor submarine landslides, an alternate foaming cement slurry program will be activated. When the red warning occurs, an emergency evacuation program should be adopted.

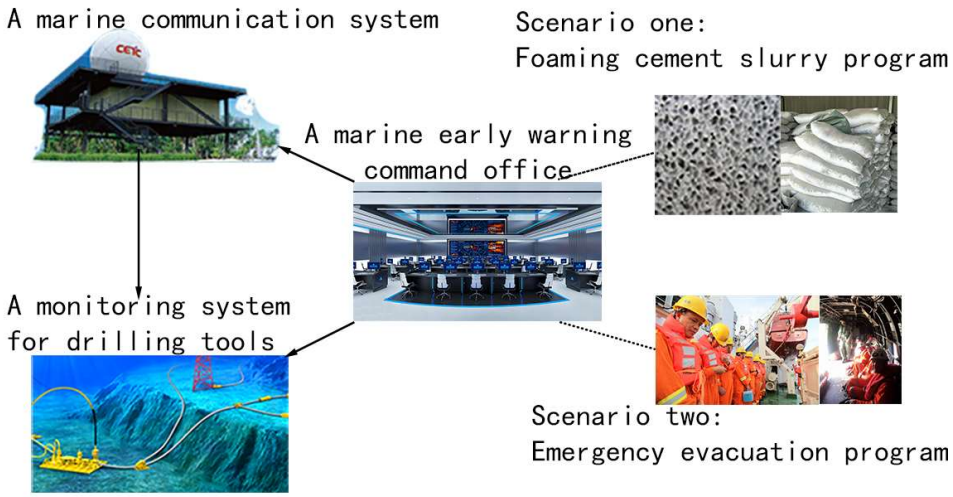


Figure 11. Early risk warning mechanism for submarine NGH drilling.

4.3. Improving Safety Regulations Through Legal Supervision

The United Nations Convention on the Law of the Sea (UNCLOS) has been widely recognized as the constitutional law of the sea since 1982. The International Seabed Authority (ISA) was established in 1994 to regulate mining and related activities in the international seafloors beyond national jurisdiction, an area that includes most of the world's oceans. However, there is still a blank in the Convention regarding NGH mining. In the future, it is necessary to clarify the mining scope and related responsibilities through international legislation. After registering the ownership of NGH in different regions, the authority of each country should be stated. It is strictly forbidden for any country to mine submarine NGH without taking any risk precautions.

Strict implementation of production safety is also an important safeguard against geological risks. In July 1988, the British Petroleum platform "Parpo Alpha" exploded because of natural gas leakage during the drilling process. The accident would not have happened if the rig had been overhauled before and during production.

5. Conclusions

NGH will be an important replacement energy source in the future due to its abundant reserves and clean nature. However, NGH may cause various natural geological hazards and secondary geological accidents during the extraction process. Some preliminary technical precautions and policy suggestions have been proposed to reduce the potential risks from the viewpoint of Earth system science systems (Table 4).

Table 4. Geological hazards in NGH mining with precautions and policy suggestions.

Geological Hazards		Technical Precautions	Policy Suggestions
Natural geological hazards	Stratum subsidence	Optimize CO_2-EGR method to alleviate stratum subsidence	1. Founding a risk identification mechanism through marine science and technology research; 2. Establishing a risk warning mechanism through international cooperation; 3. Improving safety regulations through legal supervision.
	Seafloor landslide	Fill foamed cement to control seafloor landslides	
	Greenhouse effect	Improve drilling technology to mitigate greenhouse effect	
Secondary geological accidents	Sand piping	Install new solid–liquid separator to reduce sand piping	
	Well blowout	Adopt new inhibitor to lower well blockage	
	Wellbore instability	Use a low-temperature drilling fluid to keep wellbore stable	

(1) There are two types of potential geological risks in commercial mining: natural geological hazards, including stratum subsidence, seafloor landslides, and the greenhouse effect; and secondary geological accidents, including sand piping, well blowout, and wellbore instability.

(2) Technical precautions include optimizing the CO_2-EGR method to alleviate stratum subsidence; filling with foamed cement to control seafloor landslides; improving drilling technology to mitigate the greenhouse effect; installing a new solid–liquid separator to reduce sand piping; adopting a new inhibitor to lower well blockage; and using a low-temperature drilling fluid to keep the wellbore stable.

(3) Policy suggestions include founding a risk identification mechanism through marine science and technology research; establishing a risk warning mechanism through international cooperation; and improving safety regulations through legal supervision.

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