New Steps to Deep-Water Hydrate Long-Term Mining by Formation Stabilization

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Abstract: The decomposition of hydrates can cause serious sand production and collapse problems, hindering the long-term effective production of hydrates. This study proposes a theory for framework reconstruction and reinforcement for deep-water hydrate layers based on grouting fracturing technology and chemical sand control principles. The setting liquid was injected via fracturing and grouting to form several cracks with a certain depth and width. The setting liquid remains in the fracture and solidifies to form a “reconstruction body.” Simultaneously, the setting liquid permeates and diffuses from the cracks to the surrounding hydrate layer, bonding with the sediment and forming a gradient solidification zone to achieve solidification and reinforcement of the hydrate layer. To achieve effective production of hydrates, the reconstruction body must consider internal reinforcement, sand control, and good permeability. The parameters of the reconstruction body were designed based on the geological characteristics of hydrate formation in a certain area. In order to effectively support the hydrate layer, the reconstruction body was designed with a 24 h compressive strength of at least 3.20 MPa and a long-term compressive strength of at least 17.70 MPa. To ensure that the permeability characteristics of the reconstructed body meet production needs, the permeability of the reconstructed body must be greater than that of the hydrate layer. The maximum concentrated pore size of the skeleton reconstruction body is designed to be 9 µm based on the particle characteristics of shale sand in hydrate reservoirs. This study provides a new approach to solving sand production and collapse.

Keywords: hydrate layer sand production; hydrate layer reinforcement; skeleton reconstruction body; strength; permeability

1. Introduction

A natural gas hydrate, which consists of only alkanes and water, is a white solid crystalline substance formed by the interaction between water and natural gas in a low-temperature and high-pressure environment. It is a cleaner energy fuel that primarily generates carbon dioxide and water after combustion. Compared to fossil fuels, such as coal and oil [1,2], it emits less carbon dioxide for the same volume. It has the advantage of large energy reserves; according to detection results [3], the total world reserves of hydrate resources are approximately $2 \times 10^{16}$ m$^3$. It has enormous heat energy, which is equivalent to twice the total heat energy of globally known coal, oil, and natural gas. Many advantages have made the extraction of natural gas hydrates a key focus in the energy development plans of various countries.

With global attention and research on natural gas hydrates, numerous results have emerged, and trial production engineering has achieved phased breakthroughs. A number of countries worldwide have conducted national-level exploration and pilot production of natural gas hydrates, including the Mesoyaha gas field in the former Soviet Union [4], Mallik [5] in Canada, the north slope of Alaska in the United States [6,7], the Nankai trough
in Japan [8], the Shenhu and Dongsha sea areas in China [9,10], the Green Canyon in the northern Gulf of Mexico [11], and the offshore areas of Ukraine [12].

However, the extraction of natural gas hydrate energy has not yet achieved commercialization, long-term efficiency, or safety. Since the 21st century, several trial production operations have been suspended because of loose formations and large amounts of sand production.

The effective trial production time of the Mallik2L-38 project in Canada was less than 30 h, and sand production from the wellbore blocked the electric submersible pump, ultimately forcing the trial production operation to terminate [5]. The hydrate project on the northern slope of Alaska in the United States produced 24,211.04 m$^3$ of gas and 10.63 m$^3$ of sand during the pilot production period, and the gravel produced caused pump wear. After six consecutive days of stable gas production in Japan, the pressure at the bottom of the well rapidly increased, and a large amount of formation sand flooded the wellbore, forcing the termination of the trial production operation. In 2007 and 2013, drilling operations in the Shenhu and Dongsha areas were conducted in China, successfully achieving breakthroughs in hydrate trial production capacity. However, because of severe sand production issues, the trial production time was only 30 days. Although various countries have also adopted measures, such as screen tube sand control and open-hole gravel–sand control during trial mining, the problems of sand production and collapse during the mining process seriously restrict the efficiency of hydrate mining.

There has been relatively little research on sand control in hydrate layers, and previous research has mainly focused on the analysis of sand particle production patterns and the migration of loose sand. Changyin et al. [13] constructed a particle-scale sand particle structure model for natural gas hydrate reservoirs and based on this, simulated the micro sand production process and morphology at the particle scale of natural gas hydrate reservoirs. The sand production mechanism and sand production morphology were studied. Murphy et al. [14] studied the sand production behavior of loose and dense sand layers based on the first marine hydrate production experiment in Japan. The results showed that under the action of a uniform fluid, the loose sand body moved as a whole, whereas the compacted sand body produced sand locally. They also found that sand production was closely related to reservoir porosity and confining pressure. Under high reservoir porosity conditions, the main driving force of mud and sand production was the drag force of the fluid, and when the confining pressure was high, the resistance of the fluid was relatively high, leading to the production of more sand.

Currently, sand control research is mostly focused on conventional oil and gas wells, whereas shale fine sand hydrate reservoirs have characteristics such as poor cementation, shallow burial, high clay content, and low permeability. However, it is not known whether the evolutionary mechanism of sand production is consistent with conventional oil and gas wells. Therefore, further research is needed to effectively control sand in the hydrate layers.

Some scholars [15–18] adopted CO$_2$ sequestration for reservoir transformation. There are four main methods for CO$_2$ sequestration: (1) geological structure sealing; (2) chemical sequestration: Transforming CO$_2$ into thermodynamically stable minerals or bicarbonate brine through a chemical transformation; (3) deep sea sequestration: Injecting carbon dioxide into the deep sea to form high-density liquid carbon dioxide lakes; and (4) seabed sediment sequestration: Injecting CO$_2$ into seafloor sediment to seal it in sediment pores. Although these storage methods have good feasibility, they pose significant technical challenges to cement deep-water environments.

At the same time, to meet the long-term development requirements of deep oil and gas and avoid the problem of formation collapse during the mining process, Bu et al. [19] proposed a cementing formation solidification integrated fluid for deep-water weakly cemented formations based on the formation characteristics of shallow weakly cemented and hydrate layers and provided a gradient layer simulation device for the cementing strength of deep-water weakly cemented formations [20]. Du et al. [21,22] proposed the concept of “gradient solidification” for weakly cemented formations, which involved
developing a gradient-enhanced cementing fluid with a particle size much smaller than the formation particle size. By utilizing the difference in pressure between the cementing fluid and the weakly cemented formation (which can be controlled based on the increase in density and height), the excess cementing formation solidification can be hydraulically injected into the formation and solidified. At the same time, it does not cause damage to shallow hydrates, forming a strength gradient structural system near the wellbore in the weakly cemented deep-water strata, providing support for the strata. However, the current research mainly focuses on the stability of the near-wellbore zone in weakly cemented formations in deep water, without in-depth research on the extraction process of hydrates. Existing studies use only small particles for solidification, leading to a decrease in porosity in the reinforcement area that hinders the flow of hydrate decomposition gas, which cannot ensure the long-term effective development of hydrates. However, this study provides inspiration for the reinforcement concept of strata for long-term hydrate layer mining.

Hydrate trial production engineering and related laboratory studies have shown that the hydrate extraction process is accompanied by sand production and formation collapse, which seriously hinder the commercial development of hydrates. Currently, relevant research is still in its early stages, and there is little research on balancing hydrate mining and maintaining formation stability. Conventional methods, such as mechanical and chemical sand control, are still used for sand control in hydrate layers [23]. The geological characteristics of the hydrate layers indicate that conventional sand control methods cannot meet the requirements of long-term effective mining. Therefore, this study intends to address the issues of accidents that occur during the hydrate trial production process, analyze the reasons for the failure of hydrate trial production, reveal the factors influencing sand production and collapse in the hydrate layers, and propose targeted solutions to prevent sand production and collapse. The research and design of skeleton reconstruction body parameters that meet the reinforcement requirements of hydrate layers will lay the foundation for long-term and efficient hydrate production.

2. Risk Analysis of the Gas Hydrate Exploitation

2.1. Hydrate Trial Production Plan

Hydrate reservoir extraction technology has been widely studied since the 1990s. Currently, multiple natural gas hydrate trial production experiments have been conducted worldwide, and analysis of the results shows that the extraction of natural gas hydrate reservoirs is technically feasible. However, there is still a long gap between industrialization, safety, and long-term large-scale production, and related research is still in the laboratory simulation stage. Based on the current hydrate trial production engineering and laboratory research progress, the main mining technologies include thermal stimulation, pressure reduction, chemical agent injection, and gas displacement.

1. Thermal recovery [23]

Thermal recovery, also known as the “heat injection method”, uses heat transfer, electromagnetism, and other methods to increase the temperature of the hydrate layer above the equilibrium temperature of the hydrate phase, causing the hydrate to decompose and release natural gas. The injection of hot fluids (steam and hot water) and electromagnetic heating are the main methods. The thermal shock method can provide continuous external heat for the rapid decomposition of hydrates; however, it has the disadvantage of significant heat loss.

2. Depressurization [24]

Depressurization is a method of reducing the pressure on the hydrate layer below the phase equilibrium pressure of the hydrate, causing the hydrate to decompose and release natural gas. The depressurization method has the characteristics of simplicity and good economy and is currently the most feasible method for the large-scale development and utilization of hydrate reservoirs. However, the depressurization method can easily lead to ground subsidence and the secondary formation of hydrates. For hydrate reservoirs with
temperatures close to or below 0 °C, the depressurization method should not be used, as it may cause the decomposed water to freeze and block the formation.

3. Chemical reagents [25]

Chemical reagents are used to inject chemical agents such as methanol, ethylene glycol, and salts into the hydrate layer to change the phase equilibrium conditions of the hydrate and cause it to decompose and release natural gas. When the chemical agent comes into contact with the hydrate, it causes decomposition of the hydrate, which can significantly reduce the initial decomposition energy of the hydrate; however, the cost is relatively high.

4. Gas displacement [26]

Thermal recovery, depressurization, and chemical reagents all change or disrupt the phase equilibrium of hydrates, rendering them thermodynamically unstable and causing them to decompose and release natural gas. As hydrates are often part of the rock skeleton, their decomposition can easily damage geological structures and induce geological disasters. However, the gas replacement method enables the development and utilization of hydrates by replacing guest molecules, which can maintain the stability of the geological structure.

5. Combination of different methods [27, 28]

Single-mining methods have limited effectiveness and many drawbacks. The combination of several methods can overcome the shortcomings of a single method and improve its effectiveness. For example, using a combination of pressure reduction and heat injection methods can effectively improve mining efficiency and reduce the risk of water freezing and blocking the formation, which can result from using only the pressure reduction method.

2.2. Accidents Occurred in Hydrate Trial Production

The earliest hydrate trial was conducted in the Messoyakha gas field in the former Soviet Union and began production in 1967. The depressurization and injection method was used, with a production time of 17 years. This is the only successful commercial hydrate project. In the later stages of mining, owing to the excessive production pressure difference, the weakly consolidated hydrate formation skeleton was broken, resulting in a small amount of bedrock sand entering the wellbore. The hydrate extraction gas field contains reservoirs in permafrost layers, which is not of great reference value for the extraction of deep-water hydrate reservoirs.

The Mallik Natural Gas Hydrate Survey and Research Project, established in the Canadian delta marsh, used thermal injection and depressurization methods for trial production in 2002, with a cumulative gas production of 470 m³ over five days. Despite the use of mechanical sand control methods, serious sand production problems still occurred during the trial production process. In a trial production project in 2007, the completion method of depressurization mining and casing perforation was adopted, and sand control screens were subsequently installed, but stable production was only maintained for 6 days. From the Mallik hydrate trial production project, researchers have realized that solving the problem of sand production in the hydrate layers is the key to achieving efficient hydrate extraction.

Although sand production occurred in the wellbore when the United States conducted a hydrate production test in Alaska, it was small and did not significantly affect the production test. In 2012, the carbon dioxide replacement method was used for mining and combined with mechanical screening for sand control. During the mining period, only a small amount of extremely fine sand was intermittently produced, which had almost no interference with the trial mining operations. The production cycle was approximately 30 days, with 24,197 m³ of communist gas. However, this method has lower mining efficiency and higher cost.

In Japan, a vertical gravel open-hole completion method was used for hydrate production testing, and sand control screens were installed. After six days of continuous and stable production, the cumulative gas production reached $1.2 \times 10^5$ m³, with a sand production of 30 m³. Subsequently, owing to the low strength of the annular filling gravel, it was
unable to continue supporting the formation, resulting in a large amount of water and sand production at the bottom of the well. As a result, the wellbore began to collapse, resulting in the failure of the trial production operation. Later in 2017, the latest GeoFORM sand control system was used, which achieved significant sand control effects and extended stable mining time, with a cumulative gas production of $2.35 \times 10^5$ m$^3$, but one of the production wells still experienced sand production.

China has also conducted numerous hydrate reservoir exploration and trial production studies. Although much research has already been performed, it is still in the trial production research stage. After extensive simulation experiments, the first production operation trial was conducted in 2017 in the South China Sea. With the help of self-developed sand control technology, gas production remained stable throughout the trial production period, and the daily gas production reached $1.6 \times 10^4$ m$^3$. In the second trial production operation in 2019, horizontal well mining technology was attempted, and it was combined with self-developed sand control technology to create a continuous gas production for 30 days, with a daily gas production of $2.87 \times 10^4$ m$^3$. However, in the later stages of the trial production, as the decomposition radius expanded, the flow resistance increased further, and even though the production pressure difference continued to increase, it could not compensate for the decline in production. This has resulted in high hydrate extraction costs and an inability to achieve commercial extraction.

2.3. Analysis of the Causes and Factors of Trial Production Accidents

It is evident from multiple global hydrate trial production projects that the problems of sand production and the collapse of hydrate layers seriously hinder the long-term development of natural gas hydrates. Although there has been significant progress in the mining technology of hydrates and the physicochemical properties of seabed sediments, there are still many problems with achieving long-term commercial mining. Currently, the most urgent issues to be addressed are sand production and hydrate collapse during mining. To solve these problems, further analysis of the causes and factors influencing sand production and the collapse of hydrates during mining is required [29].

1. Mechanical properties

There are essential differences [30,31] between natural gas hydrate reservoirs and conventional oil and gas resources. Natural gas hydrates are stored in deep-water sedimentary or permafrost layers with shallow burial depths and narrow pressure windows and without tight formations. They have the characteristics of low hydrate layering, weak particle cementation, and low formation strength, which indicate that the structural stability of the hydrate layer itself is poor and that the hydrate development process is prone to causing problems such as formation collapse.

2. Hydrate decomposition during production

Hydrates exist in different forms in the hydrate layers. When hydrates exist as cement or in pores, their decomposition can cause varying degrees of sand production and collapse.

- **Hydrate as cement**

  When hydrate is cemented with sediment, the overall strength is high, which can play a significant role in cementing the original free sand in the hydrate layer and avoiding the free flow of free sand. During the production process, the decomposition of solid hydrates directly leads to the detachment of skeletal sand, resulting in a large amount of sand production. At the same time, the decomposition of hydrates leads to an increase in porosity, further reducing the bonding strength of the hydrate layer, which leads to the collapse of the formation under external forces, such as earthquakes or increased loads.

- **Hydrate that occurs in pores**

  The hydrates adhere to the walls of the pores and support the pore space. When solid hydrates decompose into a gas–liquid mixture in a flowing state, they cannot continue to support the pore structure, thereby reducing the mechanical bearing capacity of the
formation. Simultaneously, the water generated by the decomposition seeps and increases the water content of the wellbore formation and weakens the connections between particles. With the development of hydrates, the formation fluid begins to flow, and the fluid exerts drag on the sand particles, leading to sand production and collapse.

3. Hydrate saturation

As hydrates often play a role in cementing rock particles in formations, the higher the hydrate saturation, the closer the rock particles are cemented and the higher the formation strength. When the saturation exceeds 40%, hydrates may even envelop the entire rock particle, resulting in a significant increase in the formation strength and cohesion. During the process of hydrate decomposition and mining, the cement between rock particles disappears, and the original skeleton sand is transformed into free and loose sand [32]. After the complete decomposition of the hydrates, the rock skeleton was almost in a loose accumulation state, which collapsed and disintegrated under the influence of the production pressure difference, leading to the collapse of the hydrate layer and a large amount of sand production.

The mechanical properties of the hydrate layer, hydrate decomposition during mining, and hydrate saturation are important factors that can lead to sand production and formation collapse. From this, it can be concluded that the fundamental reasons for sand production and collapse during the extraction of hydrate layers are the destruction of reservoir structure, the reduction in medium-strength formation, and the detachment of skeleton sand caused by hydrate decomposition. The mechanical characteristics of weak particle bonding and low formation strength in hydrate reservoirs indicate that the structure of the hydrate layer itself is prone to damage. The key factors affecting the strength of sand production and collapse are the degree of particle cementation and hydrate saturation. The lower the hydrate saturation, the lower the particle cementation, and the easier it is for sand production and collapse of the formation to occur under the influence of the production pressure difference.

3. Design Ideas and Methods
3.1. New Ideas for Long-Term Production of Deep-Water Hydrate Reservoirs

In order to achieve long-term effective production of hydrates, prevent sand production and collapse during the development process of hydrate layers, and take into account the efficient exploitation of hydrates, combined with the important factors that cause sand production and collapse of hydrates mentioned above, this study proposes a novel “theory of reconstruction and reinforcement of the internal framework for long-term production of hydrate layers.” This idea is based on fracking technology and the chemical sand control principle to establish an intraformational reinforcement method that can effectively strengthen the formation and improve the production efficiency of natural gas hydrates. This method uses fracking technology to squeeze a specially made curing fluid into the hydrate reservoir in advance, uses the curing fluid to press the hydrate layer out of the fracture, and then follows the fracture network to reach the depth of the reservoir. The curing fluid remains in the fracture and solidifies to form a skeleton reconstruction body; simultaneously, the solidified liquid permeates and diffuses toward the surrounding area in the fracture, bonding with the hydrate layer and forming a gradient solidification zone, as shown in Figure 1. On the one hand, the skeleton reconstruction body has high strength, which can effectively reinforce and support the formation, enhance its stability, and prevent the formation from loosening and collapsing due to the exploitation of hydrates in the later stage. On the other hand, the solidified skeleton reconstruction body also needs to have high permeability, which can provide a seepage channel for natural gas flow and improve the extraction efficiency of natural gas hydrates. Furthermore, the skeleton reconstruction body not only ensures high permeability but also has sand blocking and prevention functions, preventing the detachment of skeleton sand that flows into the wellbore under a pressure difference, subsequently damaging equipment and interrupting mining operations.
3.2. Effect of Skeleton Reconstruction Body on Sand Control and Collapse in Hydrate Layers

1. Effect of the skeleton reconstruction body on sand control

Currently, common sand control methods can be divided into mechanical and chemical sand control [33]; however, both have technical shortcomings. Mechanical sand control methods cannot effectively prevent sand production from hydrate layers in the long term. This is because hydrate sand production is different from conventional loose sandstone sand production. The decomposition of hydrates, the cementation of rock particles, and the strength of the formation result in a decrease in the hydrate part of the formation skeleton, which leads to the loosening and failure of the formation bedrock, the detachment of rock particles, and the formation of sand. Moreover, as the hydrates are mined for a longer time, sand production becomes more severe. Chemical sand control technology mainly uses resin materials, resulting in higher sand control costs and shorter effective periods that cannot satisfy the quality assurance period for general construction operations. Simultaneously, the early strength of the skeleton reconstruction body formed by the resin is relatively low, and it cannot effectively reinforce and support the formation. After solidification, this leads to a decrease in formation permeability and an increase in seepage resistance, which is not conducive to subsequent hydrate extraction.

Based on the chemical sand control mechanism, this study proposes the preparation of a solidification fluid system that combines low-temperature early strength performance and high permeability. After fracturing into the target formation, the solidified skeleton reconstruction body replaces the hydrate-bonded free sand to reshape the formation skeleton and solidify the loose formation, thereby preventing its collapse after the extraction of natural gas hydrates. Simultaneously, its high permeability provides a circulation channel for hydrate extraction, thereby improving the efficiency of hydrate extraction. In addition, using a permeable solidification fluid system for sand control has additional advantages.

- Safe
  
  Resin sand consolidation can easily block the formation and significantly reduce its permeability. In this study, the permeable solidification fluid system to be developed adopted cement slurry for sand control, and the skeleton reconstruction body had high permeability, which can effectively prevent the formation of blockages.
- Economical

![Figure 1. A schematic of solidifying fluid in the hydrate layer.](image-url)
The permeable solidification liquid system is mainly composed of additives such as cement, permeability enhancers, and early strength agents. It has the advantages of a low price and long service life, thereby reducing the cost of hydrate development.

- **Controllable**

  The performance of the permeable solidification liquid system can be adjusted according to onsite construction requirements and the actual construction environment, thereby ensuring the reliability of the solidified formation.

2. Effect of the skeleton reconstruction body on collapse

A skeleton reconstruction body is used to solidify the hydrate layer by reshaping the formed skeleton. To avoid formation collapse during hydrate mining, the skeleton reconstruction body should have high strength and effectively support the formation after hydrate decomposition. Therefore, the strength of the skeleton reconstruction body is higher than the hydrate layer rock skeleton. On the one hand, the special low-temperature and high-pressure environment found in hydrate reservoirs implies that the solidified liquid system requires low-temperature early strength, which enables the hydrate layer to be reinforced in a short period of time, thereby reducing construction time and costs. Therefore, the skeleton stress of the hydrate layer must be calculated to determine the early strength index of the skeleton reconstruction body. On the other hand, to meet the long-term effective exploitation of hydrates, the skeleton reconstruction body also requires long-term strength and must be able to stabilize the formation under the pressure difference conditions of hydrate exploitation.

4. Results and Discussion

Compressive strength and permeability are opposing properties; an increase in permeability inevitably reduces the compressive strength of the skeleton reconstruction body. Therefore, it is necessary to design the early strength and permeability parameters of the skeleton reconstruction body based on onsite geological data. Considering that a skeleton reconstruction body is used to reshape the formation skeleton and can partially replace the hydrate cementation of the formation rock particles, skeleton stress is considered the minimum early strength of the skeleton reconstruction body. At the same time, to ensure that the skeleton reconstruction body has a high permeability, it is necessary to set the long-term permeability of the skeleton reconstruction body to exceed the average permeability of the hydrate layer by more than 100%.

4.1. Overview of Study Strata

This study considered the formation of a hydrate reservoir in a certain block as the research object, as shown in Figure 2. Based on the formation data, skeleton stress at the bottom layer of the hydrate was calculated, and an early strength standard of the skeleton reconstruction body was obtained. The preliminary design of the long-term permeability and pore size of the skeleton reconstruction body was based on the average permeability of the hydrate layer and sand particle size parameters of the hydrate reservoir mentioned in the relevant trial production literature. According to the investigation and analysis of the block [34], the thickness of the gas hydrate layer in the sea area is 10–43 m, the depth of the hydrate layer from the seabed is 155–229 m, the depth of the seawater above the hydrate layer is 1100–1250 m, the porosity of the hydrate layer is 33–48%, the saturation of the hydrate in the pore volume of the sediment is 26–48%, and the geothermal gradient of the area where the hydrate exists is 43–67.7 °C/km. The density of the seafloor sediments within the sedimentary and hydrate layers is 2.6 g/cm³, and the average salinity of the seawater in this area is 3.8%.
Using the above natural gas hydrate formation parameters as a reference object, the environment in which the hydrate is located was modeled based on the range of formation data. A schematic diagram of the natural gas hydrate reservoir is depicted in Figure 3. Stratigraphic parameters are set at a depth of 1230 m for seawater, a depth of 195 m from the seabed for the hydrate layer, a thickness of 20 m for the hydrate layer, a thickness of 10 m for the aquifer, a porosity of 40% for the hydrate layer, an initial saturation of 48% for the hydrate layer, a saturation of 52% for water, and a density of approximately 0.9312 g/cm$^3$ for natural gas hydrates. Based on salinity, seawater density was calculated to be approximately 1.024 g/cm$^3$. The stress on the rock skeleton at the bottom of the hydrate layer was calculated based on the aforementioned geological parameters, and early strength indicators were developed for the skeleton reconstruction body.

![Figure 2. A block geographic location map.](image2)

**Figure 2.** A block geographic location map.

**Figure 3.** A schematic diagram of the hydrate reservoir model.

### 4.2. Design Method and Parameter Design for Performance Parameters of the Skeleton Reconstruction Body

The early compressive strength of the skeleton reconstruction body should be higher than the stress of the hydrate layer rock skeleton; therefore, it is necessary to calculate the skeleton stress of the hydrate layer to determine the early strength index of the skeleton reconstruction body. Skeleton stress refers to the portion of the pressure borne by the rock skeleton in the formation, also known as overburden pressure. The overburden pressure
is jointly borne by the rock particles and the fluid in the rock pores [35], as shown in Equation (1):

\[ P_o = P_p + \sigma \]  

(1)

where \( P_o \) is the overburden pressure, MPa; \( P_p \) is the pore pressure, MPa; and \( \sigma \) is the skeleton stress, MPa.

Therefore, it is necessary to first calculate the overlying rock pressure borne by the bottom layer of the hydrate and the pore pressure in the rock pore and then calculate the rock skeleton stress of the hydrate layer according to Equation (1).

1. Pore pressure

The burial depth of the seafloor sediments is shallow, the compaction is weak, and the entire sedimentary layer is relatively loose. The pore water between rock particles can be regarded as interconnected and connected to the free water inside the aquifer. Therefore, the pore pressure of the seafloor rocks is the hydrostatic column pressure, which can be calculated using Equation (2):

\[ P_h = 0.00981 \times \rho_{sw} \times h \]  

(2)

where \( P_h \) is the hydrostatic pressure, MPa; \( h \) is the liquid depth, m; and \( \rho_{sw} \) is the average seawater density, g cm\(^{-3}\).

Seawater, sediment pore water, and hydrate layer water are interconnected, and the pore pressure at the bottom layer of the hydrate can be calculated using static water pressure. Assuming a seawater depth of 1230 m, a sediment thickness of 195 m, a hydrate layer thickness of 20 m, and an average seawater density of 1.024 g cm\(^{-3}\), the pore pressure of the hydrate layer was determined to be 14.5 MPa.

2. Overburden pressure

To simplify the calculation of the overburden pressure borne by the bottom layer of the hydrates, the entire area was divided into seawater, sediment, hydrate, and aquifer areas, as shown in Figure 3. Assuming that the geology of each block is uniform and the density is constant, the overlying rock pressure is mainly composed of three parts: seawater, seabed sediment, and hydrate layer pressure. The seawater and sediment parts can be regarded as a single medium, and the calculation of the pressure formed by each medium is shown in Equations (3) and (4):

\[ P_{o1} = 0.00981 \times \rho_1 \times h_1 \]  

(3)

\[ P_{o2} = 0.00981 \times \rho_2 \times h_2 \]  

(4)

where \( P_{o1} \) is the pressure caused by the seawater section, MPa; \( P_{o2} \) is the pressure caused by seabed sediments, MPa; \( \rho_1 \) is the average density of the seawater, g cm\(^{-3}\); \( \rho_2 \) is the average density of the sediment, g cm\(^{-3}\); \( h_1 \) is the vertical depth of the seawater, m; and \( h_2 \) is the thickness of the sedimentary layer, m.

Substituting the relevant data into Equations (3) and (4), the depth of the seawater was 1230 m, the thickness of the seabed sediment was 195 m, the average density of the seawater was 1.024 g cm\(^{-3}\), and the density of the seabed sediment was 2.6 g cm\(^{-3}\). According to the calculations, the seawater pressure was 12.33 MPa, and the sedimentary layer pressure was 5.00 MPa.

The third part is the pressure of the hydrate layer, which is composed of sediment, water, and natural gas hydrates. Water and natural gas hydrates are located in the pores of the sediment and can be calculated according to Equation (5):

\[ P_{o3} = 0.00981 \times D \times [(1 - \phi) \times \rho_m + \phi \times \rho_i] \]  

(5)

where \( P_{o3} \) is the hydrate layer rock pressure, MPa; \( D \) is the vertical depth of the hydrate layer, m; \( \phi \) is the porosity of the hydrate layer, \%; \( \rho_m \) is the sediment density, g cm\(^{-3}\); and \( \rho_i \) is the density of substances in sediment pores, g cm\(^{-3}\). Substituting the relevant data into
Equation (5), the density of the natural gas hydrate was 0.9312 g cm$^{-3}$, the porosity of the hydrate layer was 40%, the saturation of the water was 52%, and the saturation of the natural gas hydrate was 48%. The calculated pressure of the hydrate layer was 0.37 MPa.

Therefore, because the pressure caused by the seawater is 12.33 MPa, the pressure caused by the sedimentary layer is 5.00 MPa, and the pressure caused by the hydrate layer is 0.37 MPa; the overlying rock pressure that the lowest layer of the hydrate layer bears is 17.70 MPa.

3. Framework support stress of the hydrate layer

After the pore and overlying rock pressures were obtained, the skeleton stress of the hydrate layer was calculated using Equation (1). By substituting the overlying rock pressure as 17.70 MPa and pore pressure as 14.50 MPa in Equation (1), the skeleton stress of the hydrate layer is calculated to be 3.20 MPa.

4. Design of key parameters for the skeleton reconstruction body

- Strength of the skeleton reconstruction body

The skeleton reconstruction body was cemented with a hydrate layer, which reshaped the skeleton. Its early strength must exceed the skeleton support stress of the hydrate layer; that is, the compressive strength of the reconstruction body must reach 3.20 MPa to play a role in stratum reinforcement.

Owing to the low-temperature and high-pressure environment of the hydrate layer, the skeleton reconstruction body must have early strength characteristics. The skeleton reconstruction body was cured for 1 d under the temperature conditions of the hydrate layer environment to strengthen the formation with a compressive strength of no less than 3.20 MPa within 24 h. Considering that during the extraction of natural gas hydrates, owing to the loss of pore fluid, the pressure of the overlying strata is fully borne by the formation skeleton, the long-term compressive strength of the skeleton reconstruction body should not be lower than the pressure of the overlying strata; that is, the long-term compressive strength of the reconstruction body should not be less than 17.70 MPa.

- Permeability of the skeleton reconstruction body

According to previously published data, the average permeability of hydrate reservoirs is $2.3 \times 10^{-3} \mu m^2$. To ensure that the solidification liquid can improve the extraction efficiency of natural gas hydrates after strengthening the formation, the permeability of the skeleton reconstruction body is required to reach $10 \times 10^{-3} \mu m^2$, resulting in weak permeability from the hydrate layer itself ($1 \times 10^{-3} \text{to} 10 \times 10^{-3} \mu m^2$), which transforms into a reconstructed body with moderate permeability ($10 \times 10^{-3} \text{to} 100 \times 10^{-3} \mu m^2$), thus effectively ensuring that the permeability of the skeleton reconstruction body during the hydrate trial production process does not affect the production capacity of the hydrate.

- Pore size of the skeleton reconstruction body

The rocks of the hydrate reservoir are primarily weakly cemented argillaceous siltstone, with a particle size distribution of 3–56 μm. To ensure that the skeleton reconstruction body has a certain sand control ability and prevent fine sand from entering the wellbore as much as possible, according to Abrams’ 1/3 bridge blocking principle [35], when the sand particle size is 1/3 of the formation pore throat size, a “sand bridge” can be formed at the pore throat to play a sand control role. According to this theory, the minimum particle size of sand and gravel in the reservoir is 3 μm. Therefore, it is necessary to ensure that the maximum concentrated pore size of the skeleton reconstruction body after adding an enhancer is 9 μm. Only then can an effective barrier be formed to prevent silt intrusion into the wellbore.

When the skeleton reconstruction body obtained from this study can simultaneously meet the requirements of permeability, compressive strength, and pore size, it indicates that the solidified liquid system studied meets the skeleton reconstruction requirements for reinforcement within the hydrate layer; otherwise, it will need to be re-regulated until all three aspects are met simultaneously. The strength and permeability of the skeleton
reconstruction body at different curing times (1 d, 7 d, 14 d, etc.) are measured to determine its long-term performance under the temperature and pressure conditions of the target formation. At the same time, the correlation between ultrasonic response and the formation physical properties is established. During the production process of hydrates, the changes in hydrate layer physical properties are indirectly determined through ultrasonic response.

It is worth noting that the water depth, burial depth, permeability characteristics, and particle size of the hydrate layer in different regions vary greatly, resulting in significant differences in the compressive strength, permeability, and pore size of the skeleton reconstruction body. After the solidification liquid enters the hydrate layer, it will bond with the sediment of the hydrate layer and form a skeleton reconstruction body. This means that the physical properties of the hydrate layer will affect the properties of the skeleton reconstruction body. Therefore, the indicator parameters obtained in this study were primarily used for the reference block. If used in other areas, the design method for the skeleton reconstruction body provided in this study can be used to design skeleton body parameter standards.

4.3. Fracturing and Grouting Process

1. Cycle and flush the pipeline to check the water supply and pipeline connection of the fracturing pump;
2. High-pressure pipeline pressure test. Close the main gate of the wellhead and hold the pressure on the high-pressure pipeline, wellhead, connecting thread, oil union, etc., on the ground for 2–3 min without puncturing or leaking, which is considered qualified;
3. After passing the pressure test, open the main gate and use a fracturing truck to squeeze the reagent solution into the target layer until the pressure stabilizes. The purpose is to check whether the downhole string and tools are normal;
4. Calculate the overall amount of solidified liquid based on the reservoir operating conditions, which can be configured in batches based on the total amount and speed of pumping, combined with parameters such as the thickening time of the solidified liquid;
5. Design the pump injection pressure based on the pressure of the hydrate reservoir and the strength of the hydrate layer;
6. After the trial pressure and displacement are stabilized, fracturing fluid is injected into the well to rapidly increase the bottom hole pressure. When the bottom hole pressure exceeds the formation fracture pressure, fractures will form in the formation;
7. After fracturing, the well needs to be shut in for a period of time, which depends on the final pumping time and initial setting time of the solidified liquid;
8. After the solidification liquid solidifies, the displacement liquid will be immediately pumped in to displace all the liquid in the ground pipeline and wellbore into the cracks, preventing the remaining solidification liquid from depositing at the bottom of the well and forming blockages;
9. Wash the well and clean the remaining solidified liquid system inside the well.

5. Conclusions

After analyzing the causes and influencing factors of collapse and sand production in hydrate trial production through relevant research and theoretical calculations, this study proposes a framework reconstruction concept for the long-term reinforcement of hydrate reservoirs within the production layer and design parameters for the framework reconstruction body. The key performance evaluation criteria for solidified liquid systems were determined, and the following conclusions were drawn:

1. A reinforcement theory for deep-water hydrate reservoirs is proposed, in which solidified liquid is injected into the hydrate formation through fracturing and grouting. The liquid solidifies to form a skeleton reconstruction body and simultaneously permeates and diffuses to the surrounding area in the fracturing crack, bonding with
the hydrate layer, forming a gradient solidification zone, and achieving anti-collapse and sand control effects.

2. A design method for the performance parameters of a hydrate reservoir reinforcement skeleton reconstruction body was proposed. This method can be used to design the parameters of the skeleton reconstruction body for different regions of hydrate layers, which is of great significance for achieving long-term, safe, and effective production of hydrate reservoirs.

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