Article

Sand Production Characteristics of Hydrate Reservoirs in the South China Sea

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Abstract: The degree and amount of sand production in hydrate reservoirs is related to the selection of stable production processes, but there is currently a lack of quantitative sand production prediction research using real logging data and formation samples from hydrate reservoirs. To reveal the dynamic change characteristics of in-situ reservoirs during hydrate decomposition, and explore quantitative prediction methods for guiding production practice, it is conducted a series of numerical simulations and quantitative prediction experiments. The numerical simulations are carried out using different sand-out prediction methods by using hydrate logging data during drilling, while quantitative prediction experiments of water production and sand-out are carried out based on in-situ reservoir samples. Our experiments indicate that hydrate mining is facing a serious risk of sand-out. The particle transport in the reservoir changes from “large-channel seepage” to “umbrella seepage” and then to “uniform fine flow” as the replacement flow rate decreases. A quantitative prediction model for water and sand production is also established. As a result, our study can provide support for the advancement of technology for long-term stable production and sand control of hydrates, laying the groundwork for developing a stable production plan for natural gas hydrates in offshore areas and determining the optimal depressurisation method.

Keywords: gas hydrate; logging data; in-situ reservoir samples; produced water out-sand; quantitative out-sand prediction

1. Introduction

Presently, more than 90 per cent of China’s proven reserves of fossil energy resources are coal. The per capita oil reserves represent about 11 per cent of the world’s average, while the natural gas is only about 4.5 per cent. The shortage of oil and gas resources has become an important factor restricting the sustainable development of China’s economy and society. Natural gas hydrate (commonly known as combustible ice, hereinafter referred to as hydrate) has advantages in large reserves, and wide distribution, and therefore has been considered a potential alternative energy source in the future by the world’s major oil and gas companies, and research institutions [1,2].

Hydrates in nature are cage-like crystalline compounds formed by natural gas molecules and water under certain temperature and pressure conditions and are widely distributed in shallow sediments on the seafloor and in permafrost on land [3]. According to conservative
statistical analysis, the global hydrate resources are about $2 \times 10^5$ billion tonnes of oil equivalent, which is about twice the total carbon of global conventional fossil fuels [4], and more than 90% of them are endowed in the marine area. China’s sea area is also rich in hydrate resources. The South China Sea alone is estimated to have 74.4 billion tonnes of oil equivalent hydrate. Till now, Canada, the United States, Japan and China have conducted many onshore and offshore hydrate test mining operations [5,6], while South Korea and India have also formulated detailed hydrate test mining plans [7,8]. Particularly, the results of Japanese offshore test mining and South China Sea Shenhu Sea test mining are gratifying, and global hydrate industrialisation is progressively advancing.

However, to further realize the utilisation of hydrates, it is necessary to solve the technical bottlenecks for its safe and efficient exploitation. Hydrates in nature are mainly distributed in onshore permafrost and deep-sea sediments with harsh environments and a severe lack of infrastructure, leading to more difficulties and greater safety risks in exploration and development compared to conventional oil and gas. In particular, the hydrate-bearing strata in the sea itself have a poor degree of consolidation [9]. It is easy to induce a series of engineering problems such as reservoir subsidence, instability out of the sand, and so on, and the latter in particular has become one of the bottlenecks restricting the safe, efficient, long-term and controllable extraction of hydrates. The Mallik test mining well in Canada in 2007, the CO$_2$ replacement mining test well in Alaska, USA in 2012, and the hydrate test mining wells in the South China Sea Trough in Japan in 2013 and 2017 all had serious sanding problems, which greatly affected the efficiency of gas production and even led to the test mining having to be terminated prematurely [10]. Although the sand production from the two rounds of trial production in the South China Sea muddy silt hydrate reservoir is relatively small [11,12], the capacity decay caused by the reduction of the permeability of the sand-proof medium also restricted the stable production cycle.

The main cause of the above phenomenon is a lack of clear understanding of the risks and patterns of sand production in unconsolidated muddy silt reservoirs, resulting in the failure to adopt effective sand control techniques. In order to clarify the sand production risk of the South China Sea hydrate reservoir, to elucidate the pore change characteristics of the reservoir under gas/water/sand migration, and to explore the quantitative prediction method for water and sand production, this paper conducted relevant research using real logging data and reservoir samples.

2. Research Status Worldwide

At present, more than 10 natural gas hydrate test mining projects have been carried out in several countries, including China, and almost all of them have encountered the sand problem. The most serious ones (AT1-P, 2013, Nankai Sea, Japan) have even led to the early termination of test mining. The sand production problem has become one of the main problems affecting the long-term safe and efficient exploitation of hydrates [10] worldwide.

2.1. Numerical Simulation Study of Sand Extraction from Gas Hydrate in the Sea Area

Numerical simulation of hydrate mining sand output can play an increasingly important role in guiding production practice by obtaining the understanding and law of sand output at the ore body level based on the physical characteristics of the formation [13].

Currently, there are several simulation software based on heat transfer-fluid flow coupling, such as TOUGH + Hydrate v1.0 and v1.2 [14,15], HydrateResSim [16,17], CMG-STARS [18,19], 3D DEM [20], etc., which can be used for the prediction of gas and water production during the hydrate extraction process. Some scholars have also developed simulation software such as TOUGH + Hydrate + FLAC3D [21], CMHGS [22], Hydrate-Biot [23,24], etc., which can be used for the study of geotechnical problems related to the hydrate extraction process.

The solid particle dislodgement and transport process was hitched to a coupled heat transfer-flow-geotechnical model for hydrate mining, and the critical hydraulic gradient was used to make a judgment on whether dislodgement of solids could occur, and the
amount of particle dislodgement was correlated with the degree of shear damage to the sediment skeleton. It has been found that slowing the rate of buckling was effective in mitigating the sand output at a given mining volume [25]. In addition, the predictions obtained by using the recently developed simulation program fit the gas, water and sand output processes of the first hydrate test mining in Japan in 2013 fitted well [26,27]. On this basis, a hydrate mining out of sand simulation procedure based on the continuous-discrete medium theory was constructed by integrating TOUGH + Hydrate, FLAC3D, and PFC3D multi-software, drawing on the previous work [21], and the hydrate mining simulation software TOUGH + Hydrate was integrated with the geotechnical analysis software FLAC3D, to achieve the coupled simulation of hydrate mining heat transfer-flow-geotechnical process. The hydrate mining simulation software TOUGH + Hydrate is coupled with the geotechnical analysis software FLAC3D to achieve the coupled simulation of heat transfer-flow-geotechnical process of hydrate mining, after which the information of stress state, hydrate saturation, fluid flow rate, etc. obtained from the simulation is transferred to the discrete element simulation software PFC3D as the initial and boundary conditions to carry out the microscopic sand emergence simulation. On the other hand, some scholars used TOUGH + Hydrate and finite element analysis software ABAQUS 2017 to establish a two-dimensional bare-borehole completion model, took the critical plastic strain as the judgement criterion of sand out [28], and qualitatively analysed the influence of hydrate decomposition, mining differential pressure, reservoir temperature, reservoir permeability and other parameters on sand out by solving the multi-field coupled equations of sand out from custom hydrate mining. The simulation results show that the stress concentration in the borehole and the reduction of formation strength caused by hydrate decomposition are the root causes of sand-out of the reservoir. In addition, a gas-water-sand multiphase seepage model during hydrate extraction was constructed by using CMG-STARS software without considering the geotechnical process [19], which was used to study the performance of gas production and the amount of sand output under different sand-proofing standards, and the results showed that there were large differences in the system gas production under different sand-proofing standards, and excessive sand-proofing precision (e.g., 2–6 µm) would lead to clogging around the wellbore, which would seriously affect the efficiency of gas production. COMSOL Multiphysics was also used to simulate the gas-water production and mud-sand spalling behaviour of hydrate-bearing sediments under different buckling scenarios at a laboratory scale [29], and the results showed that the contribution of sand spalling behaviour to the expansion of the pore fluid transport space during hydrate disintegration was only 0–13.49%, and the minimum contribution of hydrate disintegration behaviour was 86.51%.

The existing numerical simulation of hydrate mining out of sand is still in the exploratory stage due to the lack of clarity on the mechanical fracturing mechanism of hydrate mud chalk reservoirs. It is easy to ignore the change of fluid-solid transport channels triggered by inhomogeneous strata under different hydrate saturation levels, as well as the carrying effect of high-yield gas flow on mud and sand, thus restricting the reliability of the simulation results in guiding the engineering practice.

2.2. Experimental Study of Natural Gas Hydrate Sand Production in the Sea Area

Due to the problems of high cost, long periods and many uncontrollable factors in hydrate field tests, indoor experiments are the main means to study the mechanism of hydrate mining and obtain the related key parameters. Hydrate mining is accompanied by complex phase and temperature changes, and the deterioration of reservoir skeleton due to hydrate decomposition will further affect sand production. Therefore, the influence of hydrate decomposition on sand production should be considered in the relevant experimental studies.

Early experiments on the sand emergence process of hydrate mining explored the effects of different temperatures, pressures, pressure drop amplitudes, pressure drop rates and other factors on the sand emergence process of hydrate mining. It proposed that the
sand emergence mainly occurs during the pressure drop process and that the driving force for the sand emergence is the flow of water in the pore space rather than the decomposition of the produced gas. In addition, the flow rate of the water has been considered a key factor affecting the strength of the sand emergence [30]. A large-scale simulation system (72 L) was then used to study the effect of microparticles (mainly clay particles) in the pore space on the gas output of hydrate mining. It was pointed out that the direction of movement of microparticles in the pore space of the sediment is mainly controlled by the direction of the fluid flow, and whether or not the microparticles cause clogging of the flow channel is controlled by the geometrical characteristics. When the diameter of the deposit particles (D) is more than 2.4–6.4 times the diameter of the flowing microparticles (d), a single microparticle can flow freely in the pore space, while when the number of the flowing microparticles increases, clogging may occur even if D/d is close to 20 [31]. Through the construction of a visual hydrate mining experimental platform, mud and sand were directly observed in the formation, but no sand production was observed during the hydrate mining process. The amount of sand produced was only 0.012% of the total amount of sand in the experiment [32]. In the same one-dimensional filled gravel column permeability experiments, no large-scale sand production was observed, but fine sand intrusion into the gravel layer was observed after increasing the flow rate [33]. The sand emergence experiments under loose sand and dense sand conditions showed that loose sand mainly moved as a whole under the action of homogeneous flow, but the sand structure was relatively stable, while dense sand was more localised and prone to form large cavities [34,35].

With the successful implementation of hydrate test mining in the Shenhu Sea area of the South China Sea, scholars have also carried out experimental studies on the sand release process of hydrate mining and explored the sand release characteristics of the muddy reservoir on the basis of the previous researchers. Among them, the study on the sand-blocking mechanism of a sieve tube and sand-blocking medium in the mud reservoir shows that the blocking process can be divided into three stages: the beginning of blocking, intensification and equilibrium [36]. The study of the sand release mechanism, sand release pattern and its influencing factors shows that hydrate decomposition will make the reservoir strength decrease greatly, and the leading edge of sand release in the production process is very close to the leading edge of hydrate decomposition, and the lower the saturation degree of hydrate, the lower the influence of its decomposition on the overall cohesive strength of the reservoir, and the more unlikely to produce sand [37]. The experiments of sand release under hydrate mining conditions were carried out for sandy and muddy non-metamorphic reservoirs, these experiments showed that the gas production rate and gas production pattern will affect the water-carrying capacity of the gas, thus affecting the amount of sand. It is recommended to carry out stage-by-stage graded sand prevention during sandy hydrate mining, i.e., to allow the output of small-grained sand at the initial stage to improve the pore-permeability conditions of the reservoir, and to strengthen the prevention and control of large-grained sand at the middle and late stages. It also helps to form effective sand arches, bridges and channels, whereas sediment morphology during mud hydrate reservoir mining is much larger and more prone to large-scale serious sand production problems [38–40]. For the hydrate reservoir in the Liwan Sea area in the northern part of the South China Sea as a reference object, the innovative proposal of using the two-channel acoustic method to monitor the distribution of solid particles in the samples. The results show that without the use of the sand-proofing device, under the production pressure difference of 1 MPa, the sand output accounted for 19% of the total amount of sand in the experiments, and the sand output problem is very serious. The best effect is achieved when $D_{50} = 11d_{50}$, $\omega = 3.8d_{50}$ ($D_{50}$ refers to the median gravel particle size, the $d_{50}$ refers to the median particle size of reservoir particles, and $\omega$ refers to the sieve size) the effect is optimal and recommended the use of 4 MPa pressure reduction and 400-mesh sand-proof screen mesh in practical mining [41]. Studies on the sand behaviour of hydrate-bearing reservoirs before, during and after decomposition show
that the amount of sand produced before hydrate decomposition is small and is dominated by muddy chalk. After hydrate decomposition, the amount of sand produced increased and was dominated by chalk, fine sand and medium sand [42].

The above experimental results show that the driving force of the sand emergence process in hydrate mining is mainly the water flow in the pore space, and the factors affecting the sand emergence process include the magnitude of the pressure drop, the rate of the pressure drop, and the saturation of the hydrate. Early studies focused on the sand behaviour of sandy reservoirs, and the sand process in sandy reservoirs was mostly controllable in the experiments. With the success of the hydrate test mining project in the Shenhu Sea of the South China Sea, more attention has been paid to the sand release behaviour of muddy reservoirs. Existing research results show that mud reservoirs exhibit a higher risk of sand emergence due to finer sediment grains. At the same time, due to the elevated mud content, the sanding process in mud reservoirs is prone to forming special structures such as “mud cake” and “mud skin” in the near-well area, which can lead to clogging problems and affect gas production.

3. Methods

This article adopts a combination of numerical analysis and experimental methods to conduct research, including:

Firstly, substituted the logging data of hydrate reservoirs into four conventional sand production prediction methods for qualitative judgment of hydrate reservoir sand production.

Then, using a sand production simulation experimental device and combining it with formation samples, a study on the sand production morphology of reservoirs under different gas-liquid flows was conducted.

Finally, collect the produced water and sand from hydrate reservoirs at different depressurisation rates, and complete a quantitative exploration study on sand production.

4. Numerical Simulation of Sand Production Based on Logging Data

To understand the mechanism and risk of sand release from hydrate reservoirs in the South China Sea, it is implemented numerical simulations of sand production based on logging data of three hydrate reservoir drilling wells in the sea area. Our method is based on the acoustic time difference method, combined modulus method, sand emergence index method and Schlumberger’s ratio method [43]. The data of reservoir density, acoustic time difference and Poisson’s ratio are substituted into the calculation formula to carry out the simulation of sand emergence from the reservoir, qualitatively determine the risk of sand emergence from the reservoir and solve the problem of determining sand emergence before the exploitation of hydrate.

The acoustic time difference method can be described by:

\[
\begin{align*}
\Delta t_v & < 312 \mu s/m, \text{ Stabilisation without sand} \\
312 \mu s/m & \leq \Delta t_v \leq 345 \mu s/m, \text{ Possibility of sanding} \\
\Delta t_v & > 345 \mu s/m, \text{ Unstable, highly prone to sanding}
\end{align*}
\]

(1)

The combined modulus method is expressed by:

\[
E_c = \frac{9.94 \times 10^5 \times \rho_r}{\Delta t_v^2}
\]

(2)

where \(E_c\) is the Yung modulus of elasticity of the rock, MPa; \(\rho_r\) is the bulk density of the formation rock, kg/m\(^3\); and \(\Delta t_v\) is the time difference of the acoustic longitudinal wave, \(\mu s/m\).

\[
\begin{align*}
E_c & > 2.0 \times 10^4 \text{ MPa, normal production wellbore without sand} \\
1.5 \times 10^4 \text{ MPa} & \leq E_c \leq 2.0 \times 10^4 \text{ MPa, slight sand production} \\
E_c & < 1.5 \times 10^4 \text{ MPa, serious sand release}
\end{align*}
\]

(3)
Sand out index method can be simplified by:

\[ B = \frac{\rho_r}{\Delta t_v} \times 10^{-10} \]  

where \( B \) is the sand out index, MPa; \( \rho_r \) is the bulk density of formation rock, kg/m\(^3\); \( \Delta t_v \) is the time difference of acoustic longitudinal wave, \( \mu s/m \).

\[
\begin{align*}
B \geq 2.0 \times 10^4 \text{ MPa}, & \quad \text{No sand or little sand in normal production} \\
2.0 \times 10^4 \text{ MPa} > B > 1.4 \times 10^4 \text{ MPa}, & \quad \text{medium level of sand production} \\
B \leq 1.4 \times 10^4 \text{ MPa}, & \quad \text{excessive sanding of stratum}
\end{align*}
\]

(5)

The Schlumberger ratio methodology is in the form of:

\[
R = \frac{(1 - 2\mu)(1 + \mu)}{6(1 - \mu)^2} \frac{\rho_r^2}{\Delta t_v^4} \times 10^{-20}
\]

where \( R \) is the Schlumberger ratio, MPa\(^2\); \( \mu \) is the rock Poisson’s ratio, dimensionless.

\[ R < 5.9 \times 10^7 \text{ MPa}^2, \quad \text{No sand or little sand in normal production} \]  

(7)

The results of the simulations are shown in Figures 1–4.

Figure 1. Sand simulation results of acoustic time difference method on wells W05A (a), W10 (b) and W19 (c).
Figure 2. Sand simulation results of combined modulus method for wells W05A (a), W10 (b) and W19 (c).

Figure 3. Simulated sand output results of sand output index for wells W05A (a), W10 (b) and W19 (c).
Whereas the simulation result of the W19 well is the lowest, showing a serious sand release when there is no hydrate cementation. The combined modulus $E_C$ parameter value of sand release in the non-aqueous material section is obviously low. Whereas the Schlumberger ratio method, which introduces Poisson’s ratio into the simulation, has a wider range of applications in the field of oil and gas in offshore sands and provides more reliable results. The results show that:

1. The Schlumberger ratio of wells W05A ($1.4 \times 10^4$ MPa), W10 ($2.05 \times 10^4$ MPa), and W19 ($7.1 \times 10^3$ MPa) show different tendencies in the hydrate production/slight sand production. The value of the hydrate layer ranges between $1.5 \times 10^4$ MPa, indicating moderate to severe sanding, and the hydrate upper and lower layers drop steeply to $3.8 \times 10^3$ MPa, which is far lower than the cut-off line of $1.5 \times 10^4$ MPa for severe sand production/slight sand production, indicating that the sand layer has a serious tendency to produce sand when there is no hydrate cementation. The combined modulus $E_C$ value of hydrate reservoir sand index value between: $6.0 \times 10^3$ $\sim$ $2.05 \times 10^4$ MPa, moderate to severe sanding, and the hydrate upper and lower layers of the sand index value. The sand index value of the formation above and below the hydrate drops steeply to $3.8 \times 10^3$ $\sim$ $5.4 \times 10^3$ MPa, which is far lower than $1.4 \times 10^4$ MPa (the interval of $1.4 \times 10^4$ $\sim$ $2.0 \times 10^4$ MPa, is moderate sanding. The value of sand index less than this range indicates serious sanding), indicating the risk of serious sanding;

2. The simulation results of well W10 have similar trends as W05A, but the value of the sanding parameter of the non-aqueous section of the simulated well is obviously low, and the simulation results of well W19 have the lowest, showing the state of serious sanding. The simulation result of the W10 well is similar to that of W05A, but its simulation parameter value of sand release in the non-aqueous material section is obviously low. Whereas the simulation result of the W19 well is the lowest, showing a serious sand release status. In summary, the simulation results show that the stability of hydrate reservoirs in the South China Sea is generally poor, and all of them are serious sand outburst formations.

**Figure 4.** Schlumberger ratio of wells W05A (a), W10 (b) and W19 (c) simulated sand results.
5. Study of Sand Emergence Phenomenon Based on In Situ Reservoir Samples

This section was mainly carried out using the device shown in the figures (Figures 5 and 6). This device could simulate the sand production morphology of weakly consolidated reservoirs with different median particle sizes ($D_{50} = 5\sim1000\ \mu m$), and record the sand production and water yield. The device consists of a micro-imaging acquisition module, a gas-liquid pumping module, a core thin-section model module and a sand collection module. The outlet of the gas-liquid pumping module is connected to the inlet of the core flake model module, the outlet of the core flake model module is connected to the inlet of the sand collection module, and the micro-imaging acquisition module is connected to the core flake model module. The position and angle of the micro-imaging acquisition module can be changed at will.

![Flowchart of the experimental setup](image)

**Figure 5.** Flowchart of the experimental setup.

![Physical diagram of the experimental setup](image)

**Figure 6.** Physical diagram of the experimental setup.

Based on the reservoir samples from Shenhu Sea in the South China Sea, research on the characteristics of sand production after hydrate decomposition in muddy chalk reservoirs was carried out. During the experiment, a simulated core (reservoir) was loaded in the visualisation cell to simulate the state of the reservoir after consolidation. Then, the driving fluid (gas/liquid) is injected into the cell at a set flow rate through 8 inlet
holes evenly distributed around the circumference of the cell, and the fluid flows in the pore space of the simulated core in the cell, which represented the process of stripping, transporting, carrying, and accumulating the particles around the pore space when the fluid flowed in the pore space of the formation. As the fluid continues to be injected, gravel detachment begins to occur at the outlet location of the thin section flow, and the formation of a sand outlet pore expands towards the inflow end of the thin section. By changing different experimental conditions, it could compare the sand transport and hole widening process under different production conditions. At the same time, it could be analyzed the sand clogging situation according to the real-time differential pressure changes. The whole experimental process can be video-recorded or photographed at any time by launching the software.

5.1. Experimental Methodology

Since the reservoir after hydrate decomposition is usually an unconsolidated formation, this experiment first does not use a cementing agent to consolidate the in-situ mud sand or formation sand. The specific experimental steps are as follows:

1⃝ Open the top cover and the window of the core thin-section model, fill the core cementing space with stratum sand and other mixtures of a certain grain size according to the requirements of the experiment, and fill the experimental thin-section model according to the density of the in-situ stratum to ensure the consistent effect of each filling;
2⃝ Install and seal the upper cover and the sight window, and connect the flake to the experimental device after the core is filled;
3⃝ Open the visual microscope and aim the lens at the visualisation window of the radial thin section model;
4⃝ Open the inflow and outflow valves of the core thin section model, and open the outflow valve of the liquid piston container at the same time;
5⃝ Open the data acquisition software and input the basic conditions and parameters of the experiment;
6⃝ Through the software control, inject the liquid of certain viscosity into the thin section model according to the set flow rate to carry out the experiment;
7⃝ Collect, dry and weigh the stratum sand brought out by the fluid after the injection process is completed, and use it for later experimental analysis;
8⃝ According to the automatically collected flow information can be calculated to inject the fluid volume;
9⃝ Clean up the residual sand and liquid in the thin-section model and end the experiment.

5.2. Experimental Conditions

The experimental reference temperature simulates the hydrate reservoir temperature around the well (set to 10 °C for this experiment); the experimental pressure condition is a low-pressure system, with the flake outlet pressure at atmospheric pressure of 0.101325 MPa, and the actual inlet pressure depends on the experimental discharge volume, the viscosity of the experimental fluid, and the porosity of the granular body within the flake.

5.3. Experimental Materials

The experiments were carried out using in-situ reservoir samples from the Shenhu sea trial, as shown in Figure 7. Its particle size analysis curve is shown below, and the measured D_{50} values are 7.29 µm, 8.93 µm, 7.87 µm, and the median average particle size is 8.03 µm, as shown in Figure 8.
(1) Sand blocking media

This experiment mainly uses the more common media types of regular filter mesh class and regular slit class, which belong to the metal cell that can be bent into a cylinder and loaded into different cell models; at the same time, it can also test the sand blocking effect of the particle filling class (ultra-lightweight ceramic grains) media.

(2) Replacement fluids

Replacement fluids include gas (N\textsubscript{2}), liquid (water) and gas-water two-phase flow replacement. The actual production process is dominated by gas-liquid two-phase flow (Table 1), so the experiment is as far as possible to take the two-phase flow for the replacement, and the other pure liquid, pure gas replacement as an auxiliary comparison verification.

Table 1. Replacement fluids and numbers.

<table>
<thead>
<tr>
<th>Type</th>
<th>Experimental Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas (N\textsubscript{2})</td>
<td>1</td>
</tr>
<tr>
<td>water</td>
<td>2</td>
</tr>
<tr>
<td>gas and water</td>
<td>3</td>
</tr>
</tbody>
</table>

(3) Replacement flow rate

Conversion method of the experimental gas volumetric rate: according to the daily gas production of 100,000 m\textsuperscript{3}/d as the base value, the downhole pressure is 15 MPa, the downhole temperature is 15 °C (288 K), the natural gas compression factor under the condition is 0.7, the gas production under the condition of high pressure of downhole is about 500 m\textsuperscript{3}/d. According to the conversion of 10,000 gas inlet holes, the average gas and water production is about 500 m\textsuperscript{3}/d. According to the conversion of 10,000 gas inlet holes, the average gas and water production is about 500 m\textsuperscript{3}/d.

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Figure 7. In-situ reservoir sediment in the Shenhu Sea test mining area.

Figure 8. In-situ sediment grain size analysis curve of hydrate reservoir in Shenhu sea area.
gas volumetric rate is 34.7 mL/min, in order to facilitate the experimental development, 20 mL/min, 40 mL/min and 60 mL/min were taken respectively.

Experimental liquid volume conversion method: according to the field test data of Shenhu sea trial mining, the liquid production at the bottom of the well is about 0.1 of the gas production, but too low injection rate will significantly prolong the experiment, so in order to balance the experimental time and the actual effect, the liquid replacement flow rate will be enlarged by 10 times, 20 mL/min, 40 mL/min and 60 mL/min were taken respectively.

With the constant gas volumetric rate, different gas-to-water ratios ($V_1 = 2, V_2 = 1, V_3 = 0.5$) were also selected as one of the sensitive factors for the experimental analysis, and the experimental scheme of the orthogonal experiment is shown in Table 2.

### Table 2. Replacement flow rates and numbers.

<table>
<thead>
<tr>
<th>Model</th>
<th>Gas Flow (mL/min)</th>
<th>Liquid Flow (mL/min)</th>
<th>Air-Water Ratio</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>radial flow cell</td>
<td>20</td>
<td>/</td>
<td>/</td>
<td>single-phase</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>/</td>
<td>/</td>
<td>drive</td>
</tr>
<tr>
<td></td>
<td>60</td>
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<td>/</td>
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<td></td>
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<td>/</td>
<td>/</td>
<td>drive</td>
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</tr>
</tbody>
</table>

The experiments used a radial cell model, which can simulate the effect of radial sand outflow and sand retaining media and is the closest to the actual process of fluid production in the formation (the model has an outer diameter of 10 cm, a thickness of 1 cm, and a pressure resistance of 15 MPa, Figures 9 and 10).

![Figure 9. Experimental radial thin section body model.](image9)

![Figure 10. Schematic diagram of the radial cell model.](image10)
The volume of the filled sample area is 87.9 cm$^3$, and the mass of the filled sample is 172.3 g according to the density of the hydrate stratum in the Shenhu Sea of the South China Sea, which is 1.96 g/cm$^3$, and according to the ratio of gas to water, which is 7:1, the mass of the mud and sand is 150.8 g, and the mass of the liquid is 21.5 g.

5.4. Analysis of Results

(1) Analysis of the impact of displacement flow on particulate transport

① Pure Gas Replacement Condition

20 mL/min, 40 mL/min, and 60 mL/min (pure gas) were used to flow through the simulated reservoir, and the sand production morphology was observed by microscope.

When the pumping flow rate was 20 mL/min, N$_2$ was used to carry out the pure gas-phase replacement experiments, the experimental temperature was 15°C, and the replacement time was 20 min. The whole process was recorded by the micro camera system, and the flow rate and pressure were recorded by the data acquisition software. From the video recording of the whole replacement process, it can be seen that when using low-flow pure gas replacement, a few small non-uniform seepage channels will be formed around the simulated wellbore at the beginning, and with the passage of time. After extending outward for a certain distance, these small sand channels won’t collapse and expand, showing a relatively stable “fine flow” sand production pattern, and the final equilibrium state is shown in Figure 11.

![Figure 11. Photo of 20 mL/min pure gas expulsion experiment.](image)

At a pumping flow rate of 40 mL/min, N$_2$ was used to conduct pure gas-phase replacement experiments at a temperature of 15°C for 20 min, and the replacement time was 20 min. It can be seen from the video recording of the whole replacement process that at this flow rate. At the initial stage of the replacement (Figure 12a), the sand started to come out from around the near-well, and the small, irregular channels were expanded to gradually form the “umbrella” sand channels (Figure 12b). Over time, the “umbrellas” of several umbrella-shaped channels converge near the wellbore and eventually flow into the wellbore (Figure 12c), and the replacement will finally reach a stable equilibrium state, and the channels will no longer be expanded.

When the pumping flow rate is 60 mL/min, N$_2$ is used to carry out pure gas-phase replacement experiments with a temperature of 15°C, and a replacement time of 20 min. It can be seen from the video of the whole replacement process that, when the high-flow replacement is carried out, the collapse phenomenon of the near-well zone will evolve very soon around the well (which is a reference for the impact caused by non-uniform gas production during exploitation), and then the gas flow will be gradually stabilized. Once the weakly cemented part of the reservoir starts to produce sand, a dominant channel will be formed; as the macro
reaches a stable equilibrium condition, the fluid will have a greater drag force on the formation particles. This forms a dominant channel with greater fluid drag on formation particles; a stable equilibrium state will be reached macroscopically as expulsion proceeds, as shown in Figure 13.

Figure 12. Variation of photo in 40 mL/min pure gas expulsion experiments. (a) Initial status. (b) Umbrella seeage state. (c) Umbrella handles convergence state.
(c) Variation of photo in 40 mL/min pure gas expulsion experiments. (a) Initial status. (b) Umbrella seepage state. (c) Umbrella handles convergence state.

When the pumping flow rate is 60 mL/min, N₂ is used to carry out pure gas-phase replacement experiments with a temperature of 15 °C, and a replacement time of 20 min. It can be seen from the video of the whole replacement process that, when the high-flow replacement is carried out, the collapse phenomenon of the near-well zone will evolve very soon around the well (which is a reference for the impact caused by non-uniform gas production during exploitation), and then the gas flow will be gradually stabilized. Once the weakly cemented part of the reservoir starts to produce sand, a dominant channel will be formed; as the macro reaches a stable equilibrium condition, the fluid will have a greater drag force on the formation particles. This forms a dominant channel with greater fluid drag on formation particles; a stable equilibrium state will be reached macroscopically as expulsion proceeds, as shown in Figure 13.

Analysis of factors affecting different flow rates under pure liquid drive conditions

Considering the random alternation of water and gas production in the actual production process, at the end of the above gas drive experiments, the simulated reservoirs were driven using pumping flow rates of 20 mL/min, 40 mL/min, and 60 mL/min (pure liquid phase), respectively.
respectively, without replacing the samples, and the morphology of sand out of the simulated reservoirs was observed microscopically.

When pure liquid phase (water) drive with a displacement of 20 mL/min is used, it can be seen under the microscope that when pure liquid drive is used, the liquid continues to form dominant channels with the seepage channels left behind by the gas drive, but it still does not collapse and expand, eventually becoming the morphology shown in Figure 14.

![Figure 14. Photo of 20 mL/min pure liquid repellent experiment.](image)

The image obtained during pure liquid phase (water) displacement with a 40 mL/min is shown in Figure 15. Under the microscope, it can be seen that when the pure liquid phase is used for the replacement, firstly, the incoming liquid will rapidly invade the weak point (seepage channel) left by the gas drive, and when the fluid drag force increases, the original stable equilibrium is broken, and there is a small local collapse and expanding to the surrounding area, and finally, a single large pore channel is formed.

![Figure 15. 40 mL/min pure liquid drive-off photo.](image)

The image obtained during pure liquid phase (water) displacement with a 60 mL/min is shown in Figure 16. Under the microscope, it could be seen that the pumped water quickly searches for the weak point, carries the reservoir particles at a high flow rate, and first forms a sand outlet channel from the far well zone, then extends to the near well zone, and then expands circumferentially, and will reach a stable equilibrium state in the macroscopic direction as the expulsion proceeds.
It can be concluded from the above experimental results that, the particle transport in the reservoir changes from “large channel seepage” to “umbrella seepage” and then to “uniform fine flow” under the condition of pure gas displacement, with the gas displacement flow rate becoming smaller. This indicates that when the flow rate reaches a certain order of magnitude, the reservoir particle transport changes from “large channel seepage” to “umbrella seepage” to “uniform fine flow”. It further indicates that when the flow rate reaches a certain order of magnitude (especially under industrial mining conditions), the risk of sand out of the reservoir should not be underestimated, and the formation should be avoided by all means to avoid the situation of “large channel seepage” of the deficit class; and the advantages and disadvantages of the influence of the dominant channel formed by the sand out of the seepage need to be further explored, and the advantages and disadvantages of “umbrella seepage” and “uniform seepage” need to be further discussed. The “umbrella seepage” and “uniform fine flow” modes have greater advantages in improving the permeability of the reservoir; therefore, the fluid flow rate has a great influence on the sand discharge situation, and there exists a range of benign influences, in the actual
production process, if it could give full play to the advantages and take effective control means (controlling the flow rate + the amount of sand), it will greatly reduce the risk of large-scale sand discharge from the reservoir. This greatly reduces the harm caused by large-scale sand release from the reservoir.

(2) Analysis of factors influencing the water-air ratio on particulate transport

Different water/gas ratio conditions were chosen to drive the simulated reservoir separately, and the simulated reservoir was observed microscopically to produce sand morphology. The experimental results can be used as a side-by-side comparison by changing different pumping flow rates to change the amount of gas and water entering the simulated reservoir.

At a pumping flow rate of 20 mL/min, the gas-liquid two-phase replacement experiment was carried out by mixing N\textsubscript{2} with water at a temperature of 15 °C for 20 min, and the replacement time was 20 min. From the video recording of the whole replacement process, it can be seen that the perturbation phenomenon is stronger than that of the single-phase replacement and the majority of the gas passes along the contact surface between the visible glass during the two-phase replacement, due to the presence of gas and water at the same time. In addition, the simulated reservoir forms a shallower bubble-like sand outlet pore and the sand outlet pore expands from near the wellbore to the well circumference at a certain radius. Most of the gas passes along the contact surface between the visible glass and the simulated reservoir, forming a shallow bubble-like sand outlet hole, and the sand outlet hole expands from the vicinity of the wellbore to the periphery of the well with a certain radius. However, as the repulsion progresses, the channel soon stops expanding and eventually forms a stable state, as shown in Figure 17.

![Figure 17](image_url)

**Figure 17.** Gas-liquid 20 mL/min mixed replacement photo. (a) Initial disturbed state of expulsion (b) Stable state at the end of expulsion.

When the pumping flow rate is 40 mL/min, the gas-liquid two-phase replacement experiment is carried out by mixing N\textsubscript{2} and water, the experimental temperature is 15 °C, and the replacement time is 20 min. From the video recording of the whole replacement process (Figure 18), it can be seen that the gas-liquid two-phase seepage is strong, and it carries the weaker part of the formation sand to be produced after intruding into the simulated stratum; due to the flow rate increase and the formation of the channel, the flow rate will be increasingly fast and the formation sand will be carried out to form a slump after being carried out to a weak part of the wellbore. As the flow rate increases, the flow rate will become faster and faster after forming a channel, and the formation of sand will be carried out and form a collapse in the weak part, and the collapsed part extends from the wellbore to the far end.
Figure 18. Gas-liquid 40 mL/min mixed replacement photo. (a) Initial state of expulsion (b) Collapse state at the end of expulsion.

When the pumping flow rate is 60 mL/min, the gas-liquid two-phase replacement experiment is carried out after mixing with N₂ and water, the experimental temperature is 15 °C, and the replacement time is 20 min. From the video of the whole replacement process (Figure 19), it can be seen that, at the beginning of the replacement process, due to the larger flow rate and the stronger gas-liquid two-phase seepage, it can be seen that obvious infiltration can be seen in the whole process of the reservoir; then the weakly cemented stratum sands are carried and transported, and the dominant channel rapidly collapses to form a strong impact; finally the fluid continues to flow along the dominant channel, resulting in a shortfall. Then the weakly cemented formation sand is carried and transported, and the dominant channel collapses rapidly, forming a strong impact and causing a deficit; eventually, the fluid continues to flow along the dominant channel.

Figure 19. Gas-liquid 60 mL/min mixed replacement photo. (a) Initial permeability state of replacement (b) End deficit state of replacement.

In this gas-liquid two-phase drive process, the initial loading of sand samples was 150.8 g. After collection, precipitation, drying, and weighing, the final drive out of sand was measured to be 48.4 g, with a sand production ratio of 32.1%.

Overall, when the gas-liquid two-phase drive, even if the water content is lower, it will still form a larger advantageous seepage channel, which will eventually lead to the emergence of the deficit phenomenon; when the pump injection volume increases, the gas-water ratio decreases, and the liquid-phase sand-carrying effect is enhanced, and the
degree of sand release and the disturbance of the formation is strengthened, which indicates that the liquid-phase is the main factor influencing the sand release, and the gas-phase is a secondary factor.

6. Experimental Exploration of Quantitative Prediction Simulation of Natural Gas Hydrate Produced Water Out of the Sand

At present, it has become a consensus in the industry that the hydrate test mining process will face the risk of sanding. However, the existing research on gas hydrate sanding is biased towards qualitative analysis and mechanism research. Therefore, the reliability of quantitative numerical simulation of sanding still needs to be verified, so it is impossible to obtain accurate quantitative sanding prediction results. In actual production, qualitative judgement can play an auxiliary role in engineering practice and often fails to provide effective guidance in regulating pump conditions, wellhead nozzle opening, separation methods, and so on. The quantitative prediction of gas hydrate water production and sand production can more effectively guide the production practice and optimise the production parameters, which is related to the long-term stable production of gas hydrate and reservoir stability.

The amount of sand output from hydrate production is controlled by multiple factors such as man-made construction, pressure drop rate, reservoir properties, etc., which are difficult to simulate through experiments. Therefore, this experiment is intended to explore the feasibility of obtaining a quantitative sand output prediction model based on the experimental method by controlling a single variable: the pressure drop rate.

This part of the study adopts the same sampling method as the previous experiment, the experiments were carried out using gas saturation for hydrate synthesis. and the following steps are taken:

1. Pass 8 MPa methane gas in the thin-section model and leave it for 12 h;
2. Open the water cooling equipment to cool down the thin-section model and record the temperature and pressure changes in the thin-section model. After synthesising the hydrate, keep the low-temperature state and leave it for 24 h to ensure that the hydrate is fully generated;
3. Slowly inject cold water into the thin-section model body, discharge the excess methane gas and leave it for 12 h;
4. Adjust the outlet pressure using the backpressure valve, the pressure reduction rate was set to 300 min/MPa, 240 min/MPa, 180 min/MPa, 150 min/MPa, 120 min/MPa, 100 min/MPa, 90 min/MPa, 80 min/MPa, 60 min/MPa, 45 min/MPa, 30 min/MPa, 20 min/MPa, 10 min/MPa, 5 min/MPa. The hydrate will decompose to produce gas and water, accompanied by sand out;
5. The amount of water produced and the amount of sand produced after drying was measured separately after the experiment.

The pressure-temperature curves for a single set of experiments are shown in Figure 20a.

During hydrate synthesis using in-situ reservoir samples, after the hydrate phase transition point is reached, the temperature changes are small, while the pressure plummets and then decreases slowly, as shown in Figure 20b.

Pressure change curves at different time intervals indicate hydrate generation and are not taken as data reflecting hydrate generation as the temperature is affected by the water bath cycle. In the microcosmic domain of pulverised/ultra-pulverised sands, hydrate generation is characterised by free water being generated first, while adherent water attached to the surface of the particles is gradually generated as the temperature decreases, resulting in a slow decrease in pressure as shown in Figure 21.
Figure 20. Temperature and pressure change curves of single-group experiments and partial enlargement. (a) Pressure-temperature variation in a single set of experiments. (b) Pressure drop followed by a slow decrease.

Figure 21. State of particle-attached water and free water → production of hydrate from free pore water → gradual production of hydrate from particle-attached water → total production of hydrate from particle-attached water.

The amount of water produced and the amount of sand produced after drying were measured after the experiments, respectively, and are shown in Figure 22.

Figure 22. Measurement of sand output before and after the experiment.

It can be seen from Figure 23 that, under different buckling rates, water production and sand production show a good correlation. In general, when the water production is...
large, the sand production is also large, indicating that the water production is the main controlling factor leading to the sand production in the process of hydrate extraction, and the effect of sand carrying is not to be neglected when the gas production reaches a certain scale. With the gradual slowing down of the rate of pressure reduction, the overall trend of water production and sand production first increases then decreases, then increases and gradually stabilises. It is shown that there are optimal buckling intervals under different buckling schemes, which are related to the mechanisms of stratigraphic deterioration.

Based on this water production and sand output model, a straight well is exploited as an example, with a 20 m sand-proof section, a 9-5/8” screen pipe completion and a pressure reduction rate of 0.5 MPa/h.

The inner radius of the filled sample area is 1.3 cm, the outer radius is 5.0 cm, the volume \( V_1 = 87.9 \text{ cm}^3 \), and the water yield is \( M_1 \). The corresponding scale of influence of the straight well is 0.47 m in radius, \( V_2 \) in volume, and \( M_2 \) in water yield, according to the principle of similarity:

\[
\frac{V_1}{V_2} = \frac{M_1}{M_2}
\]

where, \( V_1 \) experimental model volume, \( \text{m}^3 \); \( V_2 \) mining well model volume, 12.97 \( \text{m}^3 \) (outer radius of 0.47 m, inner radius of 0.12 m, length of 20 m of the annulus), \( \text{m}^3 \); \( M_1 \) predicted model water production, which is 0.10357 kg by checking Figure 23; \( M_2 \), mining well model water production, which is 15.28 \( \times 10^3 \) kg, i.e., 15.2 \( \text{m}^3 \) of water. Similarly, the sand output is 0.63 \( \times 10^3 \) kg, which is the original sand output without sand control measures. According to the experience of sand control design, the sand output after sand control is generally 1/10 of the original sand output, so the final sand output from the wellbore is 63 kg. Through exploratory experiments on water production and sand production, as well as the formation of search charts, support can be provided for the development of later hydrate trial production, plugging and permeability enhancement processes, and pressure reduction plans.

**Figure 23.** Quantitative experimental data and phenomena of water and sand production from natural gas hydrate.
7. Discussion

This article focuses on three aspects of research on the sand production characteristics of hydrate muddy silt reservoirs.

1. In terms of sand production simulation in hydrate reservoirs, different methods of sand production simulation using logging data have yielded results consistent with existing research, all of which suggest that hydrate reservoirs in the South China Sea are prone to sand production.

2. In terms of the sand production morphology of muddy silt, this article uses hydrate formation samples from the South China Sea and observes the “Umbrella seed page state” and “Umbrella handle convergence state” in Figure 12 through experiments. This indicates the process of changes in the pore structure around the wellbore during hydrate extraction. This is somewhat different from models such as earthworm-like wormhole-like and continuous collapse commonly mentioned in existing research.

3. In terms of quantitative exploration of water and sand production, although this article has conducted preliminary explorations through multiple experiments, only preliminary analysis has been carried out, and there is no clear understanding of the regularity. At the same time, there are almost no studies of the same type. The reason for this is that undigested hydrates, as part of the reservoir skeleton, degrade the mechanical properties of the reservoir after decomposition, along with the multi-field evolution of Temperature-Hydrology-Mechanics-Chemistry, making it difficult for existing theories to guide experiments and extraction. Further theoretical analysis and experimental research are needed to establish a quantitative model for water and sand production during hydrate extraction, providing support for the development of stable production plans.

8. Conclusions and Recommendations

In summary, the pressure drop rate and water production are the main factors affecting sand production. There is a coupling effect between them. The technical difficulties of hydrate sand prevention compared with that of conventional oil and gas development are mainly reflected in the fine grain size and high mud content of the formation sand. The favourable factor is that the sand-carrying performance of gas-water flow is significantly weaker than that of crude oil. In addition, compared with the sand-carrying gas-water flow, the carrying capacity of low-production gas is weaker than that of agglomerated wetted fine particles. Therefore, reservoir water content is one of the key factors limiting the effectiveness of sand control in hydrate test mining. The permeability and flow rate increase will increase the sand carrying capacity of the fluid with water output as a carrier and replacement flow as a carrying power. When the replacement flow rate becomes smaller, the reservoir particle transport from the “large-channel seepage” to the “umbrella seepage” and then to the “uniform fine flow”. “Uniform fine flow”. In the actual production process, it should be controlled by the influencing factors such as differential pressure and flow rate, and the lowering amplitude and period, in order to minimize the unfavourable factors of sand discharge and improve the gas production by penetrating the reservoir permeability under the mode of uniform fine flow. Our major findings can be summarized as:

1. The hydrate reservoirs in the South China Sea belong to unconsolidated strata, and will face the risk of sanding or serious sanding under mining conditions;

2. As the replacement flow rate becomes smaller, the reservoir particle transport changes from “large-channel seepage” to “umbrella seepage” and then to “uniform fine flow”, which indicates that the risk of reservoir sand outflow due to large-channel seepage is not to be underestimated when the flow rate increases to a certain order of magnitude (especially under industrial mining conditions).

3. When gas and liquid phases coexist, the disturbance to the formation is greater than that of the single-phase displacement process, and its pore sand morphology and particle transport pattern are also different from that of the single-phase flow. Fluid flow and gas-liquid ratio are the key factors affecting particle transport.
When the pressure reduction rate is lowered to a certain range, the rate of sand and water production no longer decreases significantly but tends to be constant, and there is an optimal interval for the pressure reduction rate. It is possible to establish a quantitative prediction model of water production and sand output through experiments, and orthogonal experiments with multiple parameters can be carried out in the future to enrich the quantitative prediction model of sand output and provide guidance for the implementation of test mining.

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