Sand production behaviors during gas recovery from sandy and clayey-silty hydrate-bearing sediments: A comparative analysis

Fulong Ning1,2,3 | Xiangyu Fang4 | Zhichao Liu1,3 | Yanjiang Yu5 | Yanlong Li2,6 | Linjie Wang1,3 | Hongfeng Lu5 | Jiaxin Sun1,3 | Xinxin Cao1,3 | Haoxian Shi5

1Faculty of Engineering, China University of Geosciences, Wuhan, Hubei, China
2Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China
3National Center for International Research on Deep Earth Drilling and Resource Development, Wuhan, Hubei, China
4Anhui Nuclear Exploration Technology Central Institute, Wuhu, China
5MLR Key Laboratory of Marine Mineral Resources, Guangzhou Marine Geological Survey, Guangzhou, China
6The Key Laboratory of Gas Hydrate, Ministry of Natural Resources, Qingdao Institute of Marine Geology, Qingdao, China

Abstract

Sand production is a crucial geotechnical issue for safe and efficient gas recovery from natural gas hydrate (NGH) reservoirs. Although the same gas production method of depressurization was chosen for the production trials in the Nankai Trough and the Northern South China Sea, their sand production behaviors differed greatly due to the skeleton diversity of sand in the Nankai Trough and clayey-silt in the Northern South China Sea, which resulted in different sand control and sand production characteristics. In this study, we conducted experiments to compare sediment responses and sand production behaviors from these two typical gas hydrate-bearing sediments (GHBSs) before, during, and after hydrate dissociation. The results reveal the fluid and sand production rates in both GHBSs are relatively low before and after hydrate dissociation. However, the sand production rate in sandy GHBS keeps stable at a relatively high value during the whole hydrate dissociation period, accompanied by a high fluid production rate and continuous sample subsidence. In contrast, the fluid and sand production rates are proved to be high only at the early stages of hydrate dissociation in clayey-silty GHBS with sand production decreasing obviously afterward, and the sample subsidence rate exponentially decay until the ultimate subsidence is reached. After experiments, two kinds of particle plugging phenomena, sand bridge and mud cake, are found to form outside sand screens in sandy and...
clayey-silty GHBSs, respectively. Differences in permeability, particle migration, and plugging characteristics are thought to be the main inducement of the variability in sand production behaviors in different GHBS types. These findings indicate that sand-production control strategies should obey geological engineering integration and differ according to the GHBS type. Specifically, we should concern sand production risk in sandy GHBS during and after hydrate dissociation, whereas more attention should be paid to the early stages of hydrate dissociation in clayey-silty GHBS.

KEYWORDS
clayey-silty reservoir, gas and water production, natural gas hydrate, sand production, sandy reservoir, sediment subsidence

1 INTRODUCTION

Natural gas hydrate (NGH) is an ice-like crystalline compound formed by water and gas molecules under high pressure and low temperature.1 NGH has attracted attention worldwide due to its wide distribution and huge energy potential.2-4 Approximately 97% of the NGH resources are distributed in the continental marine areas.5 In 2017 and 2020, China successfully carried out twice NGH field trials in the Shenhu area of the Northern South China Sea, advancing from “an exploratory production trial” to “an experimental production trial.”6-8 Japan also conducted two production trials in the Nankai Trough in 2013 and 2017, respectively.9-11 The gas hydrate-bearing sediments (GHBSs) in the Shenhu area of the Northern South China Sea and Nankai Trough are represented by clayey-silt and sand, respectively. Both the above-mentioned production results have not reached the commercial exploitation standards yet, and were reported to be impacted or even terminated by clayey-silt and/or sand production9-12 (hereinafter collectively referred to as sand production) due to hydrate dissociation, fluid flow and significantly strength weakening of the gas hydrate-bearing sediment (GHBS).13,14 In detail, different sand production behaviors were observed in these trials using the same production method of depressurization.

Considerable experiment efforts have been first made to reveal sand production behaviors and mechanisms during gas production from sandy GHBSs. The sand production was first found to be dominated by water flow by Oyama’s sand production tests,15 and the conventional commercial sand-control screens (WWS60 and WWS100) could efficiently control sand production at the laboratory scale.16 Through some preliminary laboratory results, the sand production in Japan’s first trial production is speculated to be a behavior of entire migration of the loose sand17 and that of the South China Sea had stage-by-stage characteristics.18 Most recently, Li et al. found that hydrate reformation within the sand screens causes extremely high skin effects, which in turn lead to significant gas and productivity losses.19 With the continuous successful production trials in the South China Sea, sand production behaviors from clayey-silty GHBSs have attracted scientific attention. For instance, a systematic solution was proposed to solve sand production problems during gas recovery from clayey-silty sediment.12 The subsidences in the vertical and horizontal wells of clayey-silty GHBSs would easily lead to mudflow and large-scale sand production, and a mud cake would form around the wellbore with the water production rate decreasing.20 The tests on samples from the Liwan area of the Northern South China Sea also reported that very fine silt GHBS was prone to sand production.21

The experimental work mentioned above focused either on sandy or clayey-silty GHBS separately, which are unable to be compared directly due to the different conditions of the experiments. In our recent work, we also investigated the sand production behaviors of sandy and silt GHBSs respectively,22,23 but did not compare their similarities and differences between the two types of GHBSs. Considering the fact that sandy and clayey-silty GHBS and their interlayers widely occur in the marine environment, a systematic comparison of sand production differences between the two types of GHBSs and knowledge of their mechanism leading to the difference are still necessary and important for improving management of sand production control in production operations. Additionally, sand production as a solid migration behavior is strongly coupled with fluid production and NGH reservoir deformation in space and time scales.24-26 A precise understanding of sand production behavior is
inseparable from the analysis of fluid production and sedimentation behavior of GHBSs. Herein, we investigate sand production and the corresponding gas and water production behaviors along with subsidence before, during, and after hydrate dissociation in sandy and clayey-silty GHBSs using the depressurization method. This study is conductive to better understanding the sand production characteristics of different GHBSs and selecting suitable sand control methods for target reservoirs.

2 | MATERIALS AND METHODS

2.1 | Experimental device

Figure 1 shows the customized sand production and control apparatus which was introduced in our previous work.22,23 The reactor, with an inner diameter of 120 mm and a height of 205 mm, can maintain a pore pressure up to 25 MPa, and placed in a temperature control chamber. Two PT100 temperature sensors (T1 and T2) with an accuracy of 0.1 K were installed at the center and boundary of the reactor, respectively, and the pore pressure sensors (P1 and P3) were installed at the inlet and outlet of the reactor. Axial stress was used to simulate the overlying stress which was accurately controlled by an axial-compression pump. The pore pressure in the reactor was controlled by the back-pressure pump. The outer wall of the reactor has an inlet for gas and liquid to flow in, and many small holes were evenly distributed on the inner wall to ensure that the fluid uniformly entered the reactor. A constant-flux pump injected deionized water at a certain temperature into the reactor from the constant-temperature water tank. Gas entered the gas-collecting bottle through a gas flow meter with a measurement range of 0–5 L/min. Water entered the water-collecting bottle from the bottom of the gas–liquid separator, and sand entered the sand collector through shut-off valves 1 and 2. The data acquisition system recorded the temperature, pressure, gas production rate, and subsidence during the experiment. A sand screen and a perforated supporting steel plate were installed at the outlet of the reactor. Different-sized sand screens and perforated support steel plates can be chosen for sand production tests according to the experimental requirements. The perforated support steel plate supported the samples and sand screen to ensure their stability under axial pressure during the entire experimental process.

2.2 | Experimental materials and conditions

The methane gas used in the experiment (methane purity > 99.9%) was provided by Wuhan Newradar Special Gas Co., Ltd. Deionized water was prepared using an LD-DI-Micro-20 Liding deionized water machine at our laboratory. Quartz

FIGURE 1  Schematic diagram of the experimental apparatus. (1) Distilled water tank, (2) axial-compression pump, (3) inlet valve, (4) gas cylinder, (5) pressure-regulating valve, (6) booster pump, (7) buffer tank, (8) constant-temperature water tank, (9) constant-flux pump, (10) high and low-temperature chamber, (11) visualization window, (12) shut-off valve 1, (13) shut-off valve 2, (14) sand collector, (15) reactor, (16) piston, (17) displacement sensor, (18) inlet pressure sensor, (19) axial pressure sensor, (20) outlet pressure sensor, (21) temperature sensor 1, (22) temperature sensor 2, (23) sand screen, (24) perforated supporting steel plate, (25) outlet valve, (26) back-pressure valve, (27) back-pressure pump, (28) gas–liquid separator, (29) water-collecting bottle, (30) gas flow meter, (31) gas-collecting bottle, and (32) computer
sand was purchased from Xiamen ISO Standard Sand Co., Ltd., and quartz silt was purchased from Lianyungang Hongding Quartz Co., Ltd. The clay was approximately 2500 mesh of montmorillonite and illite, provided by Hunyuan Junhong New Materials Co., Ltd. The simulated samples were prepared according to the grain size distribution curves of in situ samples cored from the Northern South China Sea and Nankai Trough. In detail, the sandy samples were screened and prepared using quartz sand. The clayey-silty samples were configured according to the mass ratio of quartz silt, clay, and quartz sand (7:2:1), whereas the clay was prepared according to the mass ratio of montmorillonite and illite (1:1). The average densities of sandy and clayey-silty samples were 1.62 and 1.68 g/cm³, respectively. The particle size distributions of sandy and clayey-silty GHBSs were obtained using a laser particle analyzer. The d50 of sandy GHBS was 208.6 μm, while that of clayey-silty GHBS was 25.7 μm (Figure 2). The sandy and clayey-silty GHBS porosity measured by a mercury porosimeter equaled 39.6% and 45.1%, respectively.

According to the sand-control criteria, the size of the sand screen should equal approximately 3.8–4.2 times the median particle size of formation sand. To better observe the sand production behavior in this experiment, the mesh size of the sand screen was enlarged. 12 mesh (1400 μm) and 80 mesh (180 μm) sand screens were selected for sandy and clayey-silty GHBS, respectively. The sand screens were approximately seven times the median particle size of the samples. A perforated support steel plate with a hole diameter of 3 mm was used for the reservoir stability. The average hydrate saturation of the GMGS6-SH02 well adjacent to the second trial production well in the Shenhu sea area of the South China Sea was 31%. Therefore, two hydrate saturation values of 20% and 30% were selected in this study. The same hydrate saturation values were also decided for sandy samples for better comparison, and the quantitative deionized water method was used to form the two types of GHBSs. The calculation of hydrate saturation was based on the following basic assumptions: (1) all deionized water was converted into hydrate; (2) the volume ratio of deionized water to hydrate was 0.87:1 (Equation 1). This volume ratio was derived from the reference values used by other researchers when testing the mechanical properties of GHBSs:

\[
V_h = V_w / 0.87, \tag{1}
\]

where \(V_h\) (L) and \(V_w\) (L) are the volumes of hydrate and water. Therefore, hydrate saturation could be estimated according to the pore water saturation in the sample as follows:

\[
S_h = V_h / V_p = V_h / V_s \cdot \Phi = V_w / 0.87 V_s \cdot \Phi = S_w / 0.87, \tag{2}
\]

where \(S_h\) (%) and \(S_w\) (%) are the saturation of hydrate and water; \(V_s\) (L) is the volume of the sample; \(V_p\) (L) is the pore volume of the sample; and \(\Phi\) (%) is the sample porosity. The equation for calculating the quantity of deionized water needed in the experiment was as follows:

\[
V_w = S_h \cdot 0.87 V_p. \tag{3}
\]

At the end of the experiment, the saturation of hydrate was calculated again from the gas produced by hydrate dissociation to contrast the saturation value calculated using the quantity of deionized water:

\[
S_h = \frac{V_g}{164 V_p}, \tag{4}
\]

where \(V_g\) (L) represents the volume of methane gas produced from hydrate dissociation.

The axial stress was maintained at 11 MPa during the experimental procedure. Before depressurization, the initial sample temperature was about 8°C, and the pore pressure was about 10 MPa. The outlet pressure was controlled by a back-pressure pump to reduce the pore pressure of the sample in the reactor. To compare the sand production behaviors of the two types of GHBSs, the depressurization rate of the back-pressure pump was set at 0.25 MPa/min; that is, the outlet pressure dropped from 10 to 0.1 MPa within 40 min. Table 1 lists the basic properties and conditions for the two types of GHBSs.

### 2.3 Experimental procedures

The experimental operation procedures are depicted in Figure 3. It includes sample preparation, water injection and displacement, depressurization and sand collection.
2.3.1 | Sample preparation

The prepared sand and clayey-silt were fully mixed with quantitative deionized water, stored for 24 h, and then placed into the reactor. The whole device was connected and then continuously injected with methane gas to remove the residual air in the reactor. Afterward, methane gas was evenly injected into the reactor, and when the inlet and outlet pressures reached 10 MPa, the \( \text{CH}_4 \) cylinder was closed. The axial-compression pump applied axial stress of 11 MPa to the sample to simulate the overlying stress of the NGH reservoir. The temperature control chamber was set to 8°C, and the formation of hydrate was observed when the temperature curve suddenly rose and the pressure curve generally dropped. During this process, the buffer tank is kept open to ensure a sufficient supply of methane gas. The hydrate growth was considered to be fully complete and all deionized water in the sample was converted into hydrate when the pressure curve no longer dropped and remained stable for over 1 h.

2.3.2 | Water injection and displacement

To better simulate the submarine GHBSs, the unconverted methane gas was displaced using deionized water to create a water-saturated system in the reactor. The back-pressure valve was set to 10 MPa, and the outlet valve was opened. The deionized water from the constant-temperature water tank at 8°C was injected into the reactor by a constant-flux pump at a speed of 6 ml/min. The displaced methane gas entered the gas-collecting bottle through the gas flow meter. When the gas flow meter showed 0 ml/min or standard cubic centimeter per minute (SCCM) for 5 min, the displacement procedure was considered to complete, and the sample was regarded as a water-saturated sandy/clayey-silty GHBSs.

2.3.3 | Depressurization

The depressurization rate of the servo back-pressure pump was set to 0.25 MPa/min to simulate a depressurization condition for gas production. During the depressurization process, the gas production rate was monitored by a gas flow meter in real-time, and the produced water was collected every 4 min. When the produced sand and clay needed to be collected, shut-off valve 1 was opened, and the sand and clay entered into the rigid pipe between the two shut-off valves. Subsequently, shut-off valve 1 was closed, and shut-off valve 2 was opened, so that sand and clay could enter the sand collector. Finally, shut-off valve 2 was closed, and the sand collector was removed for the produced sand and clay to be dried and weighed.

2.3.4 | Sand collection

In this experiment, hydrate was considered to start dissociating when temperature curves dropped during depressurization. When the temperature curves reached the lowest point, hydrate dissociation basically completed.\(^{29}\) Herein, we studied the sand production behaviors before, during, and after hydrate dissociation.

![Image](image.png)

**Figure 3** Schematic of the tested sample characteristics under different experimental operation procedures

**Table 1** Basic properties and conditions for the two categories of gas hydrate-bearing sediments (GHBSs)

| Parameters                                    | Sandy GHBS | Clayey-silty GHBS |
|-----------------------------------------------|------------|-------------------|
| Density (g/cm\(^3\))                          | 1.62       | 1.68              |
| Median particle size (\(\mu\)m)               | 208.6      | 25.7              |
| Porosity (%)                                  | 39.6       | 45.1              |
| Hydrate saturation (%)                        | 20, 30     | 20, 30            |
| Mesh size of the sand screen (\(\mu\)m)       | 1400       | 180               |
| Hole diameter of the perforated support steel plate (mm) | 3          |                   |
| Axial stress (MPa)                            | 11         |                   |
| Initial temperature (°C)                      | 8          |                   |
| Initial pore pressure (MPa)                   | 10         |                   |
| Depressurization rate (MPa/min)               | 0.25       |                   |
The first sand collection was performed when the temperature curve began to drop, corresponding to sand production before hydrate dissociation. When the temperature curve reached the lowest point, the second sand collection was performed, corresponding to sand production during hydrate dissociation. When the depressurization process was completed, the third sand collection was performed, corresponding to sand production after hydrate dissociation. We also found some sand with relatively large size during the experiments did not enter the sand collector with the water flow after passing through the sand screen and stayed in the window tube (Figure 4), the visual window components were removed after each experiment to collect the stranded sand. Thus, total four sand collections were performed during the experiment.

3 | RESULTS AND ANALYSES

3.1 | Temperature-pressure responses during depressurization

Figure 5 shows the temperature and pressure characteristics during the depressurization of sandy and clayey-silty samples with hydrate saturation of 20% and 30%. For each sample category, the temperature and pressure responses were similar under the two hydrate saturation conditions. Before hydrate dissociation, clayey-silty samples were maintained at a temperature of approximately 8°C, while the temperature of sandy samples slowly increased from 8 to 8.5°C. Such a temperature increase may be resulted from a small amount of hydrate formation when pore water and residual methane gas mixed during depressurization due to their higher permeability of sandy samples compared to the clayey-silty ones. When the outlet pressure of sandy samples dropped to approximately 7 MPa, the hydrate started to dissociate (for approximately 12 min), consistent with the hydrate phase equilibrium curve at this temperature. However, hydrate began to dissociate in clayey-silty samples when the outlet pressure dropped to approximately 5 MPa (for approximately 20 min). Such a difference in pressure is likely due to the poor permeability and corresponding slow pressure transmission in the clayey-silty samples. Although its outlet pressure dropped to 5 MPa, the actual pore pressure in the reactor was higher than the outlet pressure. As the position of the temperature sensor 1 is closer to the outlet of the reactor (Figure 1A), the hydrate around temperature sensor 1 dissociated faster and more severely than around temperature sensor 2, resulting in a sharper decrease in temperature. After hydrate dissociation (for about 32 min for sandy GHBSs; 110 and 90 min for clayey-silty GHBSs when saturation was 20% and 30%, respectively), the temperature increased very slowly due to the exchange of heat with the surroundings.

For all samples, the outlet pressure decreased from 10 to 0.1 MPa within 40 min. However, owing to the different characteristics of samples, the inlet pressure showed different depressurization characteristics. The high permeability of sandy samples caused the inlet pressure curve to almost overlap with the outlet pressure curve during depressurization. On the contrary, the clayey-silty samples with low permeability caused the inlet pressure dropped slowly before hydrate dissociation. Therefore, hydrate just began to dissociate after the depressurization for approximately 20 min. Then the sample permeability increased rapidly, and the decline rate of the inlet pressure curve suddenly spiked after the hydrate started to dissociate. The inlet pressure curve also dropped slowly to 0.1 MPa. The axial
stress was maintained at 11 MPa during all the experiments, but a small downward fluctuation of axial pressure was observed in both types of samples when hydrate began to dissociate in large quantities. This is mainly induced by hydrate dissociation which decreases in mechanical properties of the samples,\textsuperscript{32,33} and increases their effective pore space. Therefore, an obvious axial compression strain occurred under the axial loading. The axial-compression pump responded to the change in strain and discharged liquid to the piston in time to maintain the axial pressure.

3.2 | Gas and water production, and subsidence responses during depressurization

3.2.1 | Gas production behavior

Figure 6 presents the gas production behaviors of the two types of GHBSSs during depressurization. Before hydrate dissociation, all the gas production behaviors indicated very small amount of gas were produced from the residual methane gas in the samples. When hydrate in sandy samples started to dissociate, the gas production rate increased. With the decrease in the outlet pressure (Figure 5A,B), the free gas was produced continually and the gas production rate remained relatively high during the whole hydrate dissociation stage. When hydrate dissociation completed basically, the gas production rate gradually decreased and finally reached 0 SCCM. As for clayey-silty ones, high gas production rates mainly occurred in the initial stage of hydrate dissociation. Then the production rate showed a slow downward trend. When the outlet pressure reached 0.1 MPa at 40 min (Figure 5C,D), the gas production rate kept relatively stable and then decreased slowly. After hydrate dissociation, the gas production rate suddenly dropped due to no sufficient gas supply and then gradually decreased until zero. It could be found that the maximum gas production rate of the sandy sample was approximately four times larger than those of clayey-silty ones, but for the cumulative gas production, the former was a little smaller than the latter. According to the cumulative gas production, the hydrate saturations of the sandy samples were calculated to be 21.12% and 29.27% by using Equation (4), and they were 22.90% and 31.80% for clayey-silty samples, generally consistent with the
hydrate saturation of 20% and 30% calculated using Equation (2), respectively.

3.2.2 | Water production behavior

All the water production rate in sandy and clayey-silty samples were relatively low before hydrate dissociation (Figure 7). When the hydrates in the samples started to dissociate, the water production rate increased and was relatively high during the whole hydrate dissociation process. However, the increase degree of the clayey-silty samples was higher than that of the sandy one, and so does its gas production behavior mentioned before (Figure 6C,D), the former's water production rate was the highest during the initial stage of hydrate dissociation, not like the latter one which arrived the maximum during the middle stage of hydrate dissociation. After hydrate dissociation, all the water production rates dropped, and the rates of clayey-silty samples were far smaller than those of sandy samples. By comparison, the variation of water production of sandy samples was relatively small during and after hydrate dissociation, while it showed large decay trend for the clayey-silty samples. And an interesting behavior was that the maximum instantaneous water production of the sandy samples was just almost two times larger than that of the clayey-silty ones, not like four times in gas production. Besides, all of the cumulative water production after the experiments ending were almost same regardless of gas hydrate saturation and sedimentary lithology.

3.2.3 | Subsidence response

Figure 8 exhibited the subsidence characteristics of the two types of GHBSs during depressurization. Before hydrate dissociation, the subsidences of the sandy samples were larger than those of the clayey-silty ones which showed a very small variation. The reason for this behavior is that, compared to the later sample, the former sample’s permeabilities are larger and pressure propagation is relatively easier and quicker, which causes effective stresses of the samples greater increase and then induce larger subsidences. However, the subsidence speeds of the clayey-silty samples accelerated greatly and were larger than those of the sandy ones during hydrate dissociation. The greater mechanical weakening and permeability increase for the clayey-silty samples due to
hydrate dissociation are the main reasons for this behavior.\textsuperscript{34,35} Simultaneously, the effective stress continued to increase, speeding up subsidence during dissociation for both types of GHBSs. With continuous depressurization, the samples were reconsolidated and gradually restored to stability under the increased effective stress. Therefore, the subsidence speed gradually decreased. The highest subsidence rate of the sandy samples occurred in the middle stage of hydrate dissociation, while it did in the initial stage of hydrate dissociation for the clayey-silty ones, which showed a very well correlation with the fluid production behaviors shown in Figures 6 and 7. This demonstrated that the subsidences of GHBSs were controlled by the fluid flow under loading, and the maximum risk of reservoir instability may take place in the middle stage of gas recovery operation for sandy GHBSs and in the early stage for clayey-silty ones. After hydrate dissociation, the subsidence rate of all samples further decreased until it reached 0.

**Figure 7** Water production characteristics during depressurization for the sandy samples with hydrate saturation of (A) 20% and (B) 30%; and for clayey-silty samples with hydrate saturation of (C) 20% and (D) 30%.

**Figure 8** Subsidence characteristics during the depressurization for the (A) sandy and (B) clayey-silty samples with hydrate saturation of 20% and 30%, respectively. Please note that I, II, and III represent the stage before, during, and after hydrate dissociation, respectively.
Very interesting, the subsidence of the clay-silt samples increased with the hydrate saturation increase during the whole experimental procedure, however, it reversed before the middle stage of hydrate dissociation for the sandy samples. This can be attributed to the larger effective stress caused by the higher effective permeability of the sandy sample with hydrate saturation of 20% compared to that of 30%, and different hydrate growth habits between clay-silt and sandy samples under the conditions of these hydrate saturations.36,37

3.3 | Sand production behavior

Figure 9 represented sand production amounts during the four sand collection operations for the two types of samples with hydrate saturation of 20% and 30%, respectively. It could be found that there were not much differences between sandy and clayey-silty samples before and after hydrate dissociation, both the sand production increased during hydrate dissociation and decreased after dissociation. However, for the clayey-silty samples, the sand produced after dissociation decreased dramatically. In addition, the sand production amounts during hydrate dissociation and stranded in the window tube showed big differences between the two types of GHBSs. The clayey-silty samples during hydrate dissociation produced almost three times as much as the sandy samples under the conditions of the same hydrate saturation and sand control method. The stranded sand amounts in the window tube were similar, too. By observing the visualization window and subsequently analyzing the sand production behavior, the stranded sand basically belonged to sand produced during hydrate dissociation for the sandy samples and during the initial stages of hydrate dissociation for the clayey-silty samples. Overall, the sand productions of clayey-silty samples were higher than those of the sandy samples. Converted into volume, the total sand produced in the clayey-silty samples were 7.61 and 8.23 cm³, respectively, almost the same three times as much as those of 2.43 and 2.70 cm³ in the sandy samples.

Figure 10 shows the size distribution of produced sand particles. It showed a similar trend for the two types of GHBSs. Before hydrate dissociation, fluid with low drag force eroded on the samples, resulting in some unfixed fine particles migrating with the fluid. Therefore, the produced sand particles had the smallest median diameter. While the sizes of stranded sand particles were the coarsest and the sizes of produced sand came second during hydrate dissociation. After hydrate dissociation, the size of sand particles decreased again.

3.4 | Coupling relationships among sample depressurization production behaviors

Sand production from GHBSs is a multifield coupling behavior. Figure 11 presented the coupling relationships
among gas production rate, water production rate, sample subsidence, and sand production of sandy and clay-silt samples with hydrate saturation of 20% during depressurization, which was almost identical to that when the hydrate saturation was 30%. Water and sand were collected in beakers during the experiments. Strong correlations were found among the sample behaviors for either type of GBHS. With the gas and water production rates increased, the subsidences and sand production also increased. The hydrate dissociation was the fundamental reason for the increase of these behaviors, which increased the permeability and weakened the mechanical properties of the samples, and then caused the subsidence under consolidation effect. The increased subsidence also caused the effective stress increase which had a positive impact on sand production in combination with fluid flow. Meanwhile, the sand production increase conversely speeded the subsidence and influenced gas and water flow. From Figure 11, it might be concluded that controlling water production for sandy GBHS and initial subsidence for clayey-silty GBHS should be given a high-priority rating in terms of sand production control.

4 | DISCUSSION

4.1 | Sand migration and the formation of sand and clay blocks

The above results indicate that sand production behaviors differ significantly between the two types GBHSs during and after hydrate dissociation. Such a difference is probably due to the different grain sizes, mechanical and hydraulic properties, and particle plugging near the screen. When hydrate begins to dissociate, the sample’s structures are disturbed under the consolidation effect, and some free sand particles are produced. The flow of fluid, especially the flow of water, causes the migration of free sand particles and carries them to outlet. Some scholars have found that the critical fluid velocity for fine particles migration is lower than that for coarse particles, according to the balance between the moving resistance of the particles and the drag force of the fluid. In our experiments with hydrate saturation of 30%, although the maximum instantaneous water production in sandy sample is 59 ml which is larger than that of 39 ml in clayey-silty sample (Figure 7), water flow in the latter could carry more fine particles to the outlet resulting in higher sand production than that in the former (Figure 9).

When the fluid flow and stress squeeze drove sand particles to the sand outlet, some coarse-grained sand particles and attached cluster particles could not pass through the sand screen and gradually accumulated near it. Figure 12 showed the sand screens after the experiments of the two types of GBHSs. It could be found that a particle block layer was formed on the sand screen in both sandy and clayey-silty samples. The sand particles did not block the sand screen in the sand sample, while they were compact and strongly adhered to the sand screen in the clayey-silty sample, resembling a layer of mud cake to block the sand screen. These phenomena were similar to those observed by Dong et al. The differences in particle block characteristics between sandy and clayey-silty GBHSs lead to variable sand production behaviors and reservoir responses (Figure 13). The particle block in the sandy sample with coarse grain size \( d_{50} = 208.6 \mu m \) was unlikely to influence the screen permeability (Figure 12A), so the gas and water production rates remained high during and after hydrate dissociation (Figures 6 and 7). However, owing to the existence of the particle block and the

![Figure 11](image_url)
decrease in fluid velocity after hydrate dissociation, the amount and particle size of sand production decreased (Figures 9 and 10). In contrast to the responses of the sandy sample, most of the sand production in the clayey-silty sample took place in the early stage of hydrate dissociation at that time when the clay and silt had not yet formed the mud cake on the screen. With depressurization performing, the screen permeability decreased continuously, leading to a gradual decrease in the gas, water, and sand production rate. Once the mud cake occurred (Figure 12B), the sand production decreased rapidly in the late stage of hydrate dissociation and after hydrate dissociation due to lack of sufficient driving force from the fluid, especially of the water flow. Compared to the modest restriction of sand bridge with continuous risk of sand production, a tight mud cake not only restricts sand production but also severely limits the efficiency of gas production (Figure 11B), so it should be avoided and flushed inversely during production once it forms.

4.2 | Experiment-based insights into gas and sand production in the field

According to the gas and water production behaviors of the two types of samples during depressurization, it might be concluded that a high production pressure
difference for the sandy NGH reservoirs could be adopted because of its low subsidence behavior, but we should pay more attention to potentially large water and sand production behaviors, as observed in the production trials in the Nankai Trough.\(^9,11\) However, the high production pressure difference might not be suitable for clayey-silty NGH reservoirs due to its large subsidence behavior, and precise production pressure should be managed to prevent drastic hydrate dissociation. But this will further restrict the production capacity of this type of reservoir. Therefore, some stimulation techniques are required for the low-permeability clayey-silty NGH reservoirs to efficiently and stably produce gas, especially from the period of production decline during and after hydrate dissociation as shown in Figure 6C,D.

According to the sand production behaviors of the two types of samples during depressurization, it is concluded that sand-control techniques for the two types of GHBSs should be different and targeted. For sandy GHBSs, high risk of sand production often take place during the hydrate dissociation stage, especially at the middle stage (Figures 9 and 11). If adopting a gravel pack sand control method, the large drag force by fluid may cause the gravel migration and then the sand control failure, like the result of the first production trial in the Eastern Nankai Trough.\(^9\) Therefore, proper sand-control methods are critical for the successful gas production from this type of reservoir, a system like GeoFORM sand control developed by Baker Hughes used in the second production trial in the Eastern Nankai Trough may be an ideal solution if water production can be controlled in a reasonable range.\(^11\) Adopting a step-wise depressurization assisting with thermal stimulation gas production regulation may contribute to reducing the water production.\(^43\)

In contrast, the clayey-silty GHBS may adopt the gravel pack and screen completion method due to low water production rate and most sand production in a short time, that is, the initial stage of hydrate dissociation. But the mud cake effect on the gravel and the screen would greatly decline the gas production although it could also constrain sand production.\(^42\) Therefore, in some ways, the biggest challenge for this type of reservoir is not sand production but sustainable gas productivity and controllable reservoir settlement. The balance between gas production and sand production control depends on the permeabilities of gravel and screen, which is greatly influenced by clay particles and corresponding mud cake. Different clayey-silty NGH reservoirs have differences in clay type, content, silt particle size, and other characteristics, leading to different permeabilities of the gravel and screen.\(^44\) So accurate gravel and screen parameters should be designed according to the reservoir geological characteristics. The idea of holding coarse expelling fine particles (HCEFP) is an applicable guideline for the design.\(^45,46\)

At the same time, horizontal wells or multibranch wells with reservoir stimulation and composite sand control techniques for example a fracturing sand control method could be an effective way to realize the balance between gas production enhancement and sand production control.\(^47\) The composite sand control techniques may include artificial borehole walls using microbe reinforcing and chemical material forming high-permeability flow channel as well as a composite screen\(^48\) (Figure 14).

In addition, for an NGH reservoir with sand and clayey-silty interlayers, it had better adopt a combined principle of separate layer production and sand control. In a word, sand production control for NGH reservoirs is a systematic project that should be considered in the geological engineering integration of reservoir characteristics, well completion methods, sand control tools, stimulation treatment and production systems to achieve the maximum production capacity and long-term stable production. In future, it also needs to strengthen study on the interfacial interaction between sand and fluid phase and the force interaction between hydrate particles and sand particles,\(^49,50\) so as to better reveal the mechanism of sand production from GHBSs.

5 | CONCLUSIONS

We investigated the fluid and sand production behaviors from synthesized sandy and clayey-silty GHBSs to reveal the influence of skeleton type on sand production and reservoir responses under depressurization. Our work yielded the following results.

(1) The pressure propagation in the sandy GHBSs is easier and quicker than that in the clayey-silty ones under depressurization due to the former's larger
permeability. Therefore, the timing and duration of hydrate dissociation in the former is earlier and shorter, respectively, than those in the latter. The fluid, sand production, and subsidence behaviors of the two GHBS types are highly related to hydrate dissociation stages. The gas production rate, water production rate, sediment subsidence, and sand production increases when hydrate in the samples begins to decompose. For the sandy GHBSs, they increase to their maximum almost at the middle of the hydrate dissociation stage. And after hydrate dissociation, sand production continues at a relatively low level. For clayey-silty ones, the initial stage of hydrate dissociation corresponds to the peak of the gas and water production, sediment subsidence and sand production. After the hydrate dissociation, the sand production is extreme low.

(2) Except the permeability difference between the two types of samples, the sand bridge and mud cake formed outside the screen in sandy and clayey-silty GHBSs respectively is another factor that causes the differences in fluid and sand production behaviors during and after hydrate dissociation. In addition, the subsidences and sand production amounts of clayey-silty GHBSs are larger than those of sandy ones. These differences can be attributed to weaker strength and stiffness, and easier particle migration of the former. Therefore, sand-production control strategies should obey geological engineering integration and be targeted according to the GHBS type.

(3) The sand production of the two GHBS types shows a positive correlation between their gas production, water production and subsidence. According to our work, perhaps we should pay more attention to water and sand production of sandy NGH reservoirs, while to gas production and reservoir subsidence of clayey-silty ones in future field production trials.

ACKNOWLEDGMENTS
This study was supported by the Key Program of Marine Economy Development (Six Marine Industries) Special Foundation of Department of Natural Resources of Guangdong Province (GDNRC [2020]047), the National Key Research and Development Program of China (2018YFE0126400), the National Natural Science Foundation of China (No. 42006182) and the Fundamental Research Funds for National Universities, China University of Geosciences (Wuhan) (Grant no. CUGGC09).

REFERENCES
1. Sloan ED. Introductory overview: hydrate knowledge development. Am Mineral. 2004;89(8-9):1155-1161.
2. Lee SY, Holder GD. Methane hydrates potential as a future energy source. Fuel Process Technol. 2001;71(1):181-186.
3. Li IZ, Zheng M, Chen XM, et al. Connotation analyses, source-reservoir potential of unconventional assemblage types and development hydrocarbon in China. Acta Petroleli Sinica. 2015;36(5):521-532.
4. Chong ZR, Yang SHB, Babu P, Linga P, Li XS. Review of natural gas hydrates as an energy resource: prospects and challenges. Appl Energy. 2016;162:1633-1652.
5. Makogon YF, Holditch SA, Makogon TY. Natural gas-hydrates— a potential energy source for the 21st Century. J Petrol Sci Eng. 2007;56(1):14-31.
6. Li J, Ye J, Qin X, et al. The first offshore natural gas hydrate production test in South China Sea. China Geol. 2018;1(1):5-16.
7. Wu SG, Wang JL. On the China's successful gas production test from marine gas hydrate reservoirs. Chin Sci Bull. 2018;63(1):2-8.
8. Su J, Ye D, Gao C, Huang Q, Gui D. Main progress of the second gas hydrate production trial in the South China Sea. Geol China. 2020;47(3):557-568.
9. Yamamoto K, Terao Y, Fuji T, et al. Operational overview of the first offshore production test of methane hydrates in the Eastern Nankai Trough. Proceedings of the Offshore Technology Conference, Houston, Texas, USA; 2014.
10. Yamamoto K, Kanno T, Wang XX, et al. Thermal responses of a gas hydrate-bearing sediment to a depressurization operation. RSC Adv. 2017;7(10):5554-5577.
11. Yamamoto K, Wang XX, Tamaki M, Suzuki K. The second offshore production of methane hydrate in the Nankai Trough and gas production behavior from a heterogeneous methane hydrate reservoir. RSC Adv. 2019;9(45):25987-26013.
12. Li YL, Liu LL, Liu CL, et al. Sanding prediction and sand-control technology in hydrate exploitation, a review and discussion. Mar Geol Front. 2016;32(7):36-43.
13. Lu JS, Li DL, He Y, et al. Research status of sand production during the gas hydrate exploitation process. Adv New Renew Energy. 2017;5(5):394-402.
14. Li Y, Wu N, Ning F, et al. A sand-production control system for gas production from clayey silt hydrate reservoirs. China Geol. 2019;2:1-13.
15. Oyama H, Nagao J, Suzuki K, Narita H. Experimental analysis of sand production from methane hydrate bearing sediments applying depressurization method. J MML. 2010;126(8/9):497-502.
16. Lee J, Ahn T, Lee JY, et al. Laboratory Test to Evaluate the Performance of Sand Control Screens During Hydrate Dissociation Process by Depressurization. International Society of Offshore and Polar Engineers; 2013.
17. Murphy A, Soga K, Yamamoto K A laboratory investigation of sand production simulating the 2013 Daini-Atsumi Knoll gas hydrate production trial using a high pressure plane strain testing apparatus. Proceedings of the 9th International Conferences on Gas Hydrate. Denver, Colorado, USA: IGGH9; 2017.
18. Lu J, Xiong Y, Li D, Shen X, Wu Q, Liang D. Experimental investigation of characteristics of sand production in wellbore during hydrate exploitation by the depressurization method. Energies. 2018;11(7):1673.

ORCID
Fulong Ning https://orcid.org/0000-0003-1236-586X
Zhichao Liu https://orcid.org/0000-0003-2617-7333
Yanlong Li https://orcid.org/0000-0003-2859-2960
19. Li Y, Wu N, Ning F, et al. 2020. Hydrate-induced clogging of sand-control screen and its implication on hydrate production operation. *Energy*. 2020;206:118030.

20. Lu J, Li D, He Y, Shi L, Liang D, Xiong Y. Experimental study of sand production during depressurization exploitation in hydrate-silty-clay sediments. *Energies*. 2019;12(22):4268.

21. Ding J, Cheng Y, Yan C, Song B, Sun H, Teng F. Experimental study of sand control in a natural gas hydrate reservoir in the South China Sea. *Int J Hydrogen Energy*. 2019;44(44):23639-23648.

22. Fang X, Yang D, Ning F, et al. Experimental study on sand production and reservoir response of clayey silt hydrate during depressurization. *Petroleum*. Forthcoming 2021.

23. Fang X, Ning F, Wang L, et al. Dynamic coupling responses and sand production behavior of gas hydrate-bearing sediments during depressurization: an experimental study. *J Petrol Science Eng*. 2021;201:108506.

24. Yan C, Li Y, Cheng Y, et al. Sand production evaluation during gas production from natural gas hydrates. *J Nat Gas Sci Eng*. 2018;57:77-88.

25. Ning FL, Dou XF, Sun JX, et al. Progress in numerical simulation of sand production from hydrate reservoirs. *Petrol Sci Bull*. 2020;02:182-203.

26. Li Y, Wu N, Gao D, et al. Optimization and analysis of gravel packing parameters in horizontal wells for natural gas hydrate production. *Energy*. 2021;219:119585.

27. Ghiasian H, Grozic J LH. Strength behavior of methane hydrate bearing sand in undrained triaxial testing. *Mar Petrol Geol*. 2013;43:310-319.

28. Liu Z, Wei H, Peng L, Wei C, Ning F. An easy and efficient way to evaluate mechanical properties of gas hydrate-bearing sediments: the direct shear test. *J Petrol Sci Eng*. 2017;149:56-64.

29. Han H, Wang Y, Li XS, Yu JX, Feng JC, Zhang Y. Experimental study on sediment deformation during methane hydrate decomposition in sandy and silty clay sediments with a novel experimental apparatus. *Fuel*. 2016;182:446-453.

30. Atik Z, Windmeier C, Oellrich LR. Experimental and theoretical study on gas hydrate phase equilibria in seawater. *J Chem Eng Data*. 2010;55(2):804-807.

31. Wang Y, Feng JC, Li XS, Zhang Y, Han H. Experimental investigation on sediment deformation during gas hydrate decomposition for different hydrate reservoir types. *Energy Proc*. 2017;142:4110-4116.

32. Winters WJ, Waite WF, Mason DH, Gilbert LY, Pecher IA. Methane gas hydrate effect on sediment acoustic and strength properties. *J Petrol Sci Eng*. 2007;56(1-3):127-135.

33. Liu Z, Dai S, Ning F, Peng L, Wei H, Wei C. Strength estimation for hydrate-bearing sediments from direct shear tests of hydrate-bearing sand and silt. *Geophys Res Lett*. 2018;45(2):715-723.

34. Chen H, Du H, Shi B, Shan W, Hou J. Mechanical properties and strength criterion of clayey sand reservoirs during natural gas hydrate extraction. *Energy*. 2021;242:122526.

35. Wu Z, Liu W, Zheng J, Li Y. Effect of methane hydrate dissociation and reformation on the permeability of clayey sediments. *Appl Energy*. 2020;261:114479.

36. Lv J, Cheng Z, Xue K, Liu Y, Mu H. Pore-scale morphology and wettability characteristics of xenon hydrate in sand matrix-Laboratory visualization with micro-CT. *Mar Petrol Geol*. 2020;120:104525.

37. Liu Z, Kim J, Lei L, Ning F, Dai S. Tetrahydrofuran hydrate in clayey sediments—laboratory formation, morphology, and wave characterization. *J Geophys Res Solid Earth*. 2019;124(4):3307-3319.

38. Song Y, Zhu Y, Liu W, et al. Experimental research on the mechanical properties of methane hydrate-bearing sediments during hydrate dissociation. *Mar Petrol Geol*. 2014;51:70-78.

39. Yan C, Ren X, Cheng Y, Song B, Li Y, Tian W. Geomechanical issues in the exploitation of natural gas hydrate. *Gondwana Res*. 2020;81:403-422.

40. Zhou SW, Sun FJ. *Sand Production Management of Unconsolidated Sandstone Reservoir*. Petroleum Industry Press; 2010.

41. Liu HJ, Li YL, Liu CL, et al. Calculation model for critical velocity of sand movement in decomposed hydrate cemented sediment. *Mar Gas Quaternary Geol*. 2017;37(5):166-173.

42. Ru YX, Dong SX, Li Y, et al. Experimental study on sand retention mechanisms and feasibility evaluation of sand control for gas hydrate reservoirs with highly clayey fine sands. *J China Univ Petrol (Ed Nat Sci)*. 2018;42(6):84-92.

43. Guo X, Xu L, Wang B, et al. Optimized gas and water production from water-saturated hydrate-bearing sediment through step-wise depressurization combined with thermal stimulation. *Appl Energy*. 2020;276:115438.

44. Deng JG, Li P, Zhou JL, et al. Sand control optimization applied to moderately sanding wells in offshore loose sandstone reservoirs. *Acta Petrol Sin*. 2012;33(4):676-686.

45. Li Y, Hu G, Liu C, et al. Gravel sizing method for sand control packing in hydrate production test wells. *Petrol Explor Dev*. 2017;44(6):1016-1021.

46. Li Y, Ning F, Wu N, et al. Protocol for sand control screen design of production wells for clayey silt hydrate reservoirs: a case study. *Energy Sci Eng*. 2020;00:1-12.

47. Li Y, Wan Y, Chen Q, et al. Large borehole with multi-lateral branches: a novel solution for exploitation of clayey silt hydrate. *China Geol*. 2019;2(3):333-341.

48. Ning FL, Fang XY, Li YL, et al. Research status and theoretical study on gas hydrate phase equilibria in seawater. *Appl Energy*. 2020;276:115438.

49. Ning FL, Fang XY, Li YL, et al. Research status and theoretical study on gas hydrate phase equilibria in seawater. *Appl Energy*. 2020;276:115438.

50. Luo Q, Liu Z, Ning F, et al. Micromechanical tangential force distribution during hydrate dissociation for different hydrate reservoir types. *Appl Energy*. 2017;142:4110-4116.

51. Winters WJ, Waite WF, Mason DH, Gilbert LY, Pecher IA. Methane gas hydrate effect on sediment acoustic and strength properties. *J Petrol Sci Eng*. 2007;56(1-3):127-135.

52. Liu Z, Dai S, Ning F, Peng L, Wei H, Wei C. Strength estimation for hydrate-bearing sediments from direct shear tests of hydrate-bearing sand and silt. *Geophys Res Lett*. 2018;45(2):715-723.

53. Chen H, Du H, Shi B, Shan W, Hou J. Mechanical properties and strength criterion of clayey sand reservoirs during natural gas hydrate extraction. *Energy*. 2021;242:122526.

54. Wu Z, Liu W, Zheng J, Li Y. Effect of methane hydrate dissociation and reformation on the permeability of clayey sediments. *Appl Energy*. 2020;261:114479.

55. Lv J, Cheng Z, Xue K, Liu Y, Mu H. Pore-scale morphology and wettability characteristics of xenon hydrate in sand matrix-Laboratory visualization with micro-CT. *Mar Petrol Geol*. 2020;120:104525.