Protocol for sand control screen design of production wells for clayey silt hydrate reservoirs: A case study

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Abstract
The process of extracting natural gas from gas hydrate-bearing sediments (GHBS) may yield significant sand influx due to the metastable nature of GHBS. Selecting appropriate sand control media is vital to addressing the challenges caused by excessive sand production. This study proposes a protocol called holding coarse expelling fine particles (HCEFP) for sand control design. The protocol aims to provide a new optimization method for screen mesh size selection for clayey silt hydrate reservoirs. Detailed optimizing procedures of proper candidate screen mesh sizes in hydrate exploitation well in clayey silt hydrate reservoirs are depicted based on the HCEFP. Then, the site W18, which is located in the Shenhu area of the northern South China Sea, is taken as an example to illustrate the optimization procedure for screen mesh size selection. The results reveal that complete solid retention via a standalone screen is rarely beneficial as high clay contents can adversely affect wellbore productivity due to excessive plugging. Screen aperture size selection for clayey silt hydrate wells should strike a balance between retaining coarser particles and avoiding screen blockage by the relatively fine particles. Furthermore, longitudinal heterogeneity of the PSDs also increases the difficulties associated with sand control design. Multistage sand control optimization is necessary in hydrate production wells. For Site W18, we recommend that the entire production interval can be divided into two subintervals for multistage sand control operations.

KEYWORDS
clayey silt hydrate reservoir, gas hydrate, sand control, sand production, screen mesh size, Shenhu area
1 | INTRODUCTION

Natural gas hydrate (NGH) is a widely distributed unconventional resource that locates at the bottom of the fossil fuel resource pyramid.\(^1\) In the past several decades, NGH has attracted worldwide attention and enormous investments.\(^2\) The USA,\(^3\) China,\(^4\) Japan,\(^5\,6\) India,\(^6\) and South Korea\(^7\) have implemented national plans to accelerate commercial NGH exploitation.

However, the hydrate exploitation process suffers from a series of significant geotechnical problems that are caused by the metametastable characteristics of gas hydrate-bearing sediment (GHBS).\(^8\) Migration and production of sand grains, known as sanding or sand production, has become one of the significant risks that restrict the long-term and effective exploitation of NGH resource.\(^9\) This issue has remained the main preoccupation for both scientists and engineers since 2013, when Japan’s first marine hydrate exploitation trial was prematurely terminated due to excessive sand production.\(^9\,10\)

Accompanied by hydrate dissociation, the process of solid grain migration from GHBS to the wellbore is faced with a severe thermal-hydro-mechanical coupling effect,\(^12\,13\) compared with that in the conventional oil-gas industry.\(^14\) The entire sand migration process during depressurization can be divided into four substages. Firstly, grains tend to detach from the GHBS framework during hydrate dissociation.\(^16\) At the same time, the flowing fluid aggravates particle detachment, and the detached particles begin to migrate within the formation.\(^17\,18\) As a result, the migrating particles arrive at the outer boundary of the sand control media.\(^19\,20\)

These processes end up with a portion of the particles penetrating through the sand control media and arriving at the borehole.\(^21\) A thermo-hydro-mechanical coupling analytical model was provided by Uchida et al\(^22\) to illustrate the sand grain detachment and migration behaviors in GHBS. The model was applied to simulate GHBS sanding behavior both in the Nankai Trough\(^10,11\) and Krishna-Godavari basin.\(^23\) The results indicated significant influence of formation water seepage on sand migration processes.\(^24\,25\)

Besides the sanding simulation, the selection and optimal design of sand control technique are vital to addressing sand production problems in NGH production wells. It is believed that technologies developed for ultra-deepwater gas reservoirs remain overwhelmingly superior for NGH production.\(^26\) Sand control technique used in conventional gas wells can be adapted for NGH field trial operations to prevent excessive sanding. The current view in completion design for gas hydrate production is sand prevention.\(^27\) Standalone screen and gravel packing\(^28\) are two of the mainstream techniques that have been used in past NGH trials. However, for clay content over 5% in the formation sand, a thick mud cake will form around the screen during the gas-water two-phase flow.\(^29\) The mud cake increases the skin and decreases gas productivity by increasing the pressure drop around the sand control screen.

Prior studies have noted the influence of clay content on plugging.\(^30\) Particle size distribution (PSD) analyses showed that the clayey silt hydrate-bearing strata, which are widely spread in the Shenhu area of the northern South China Sea, are characterized by extremely high clay content (\(\sim 35.1\%\)).\(^31\) Therefore, screens optimized by conventional methods would suffer from serious mesh plugging in the clayey silt hydrate reservoirs. A compromise between screen plugging and sand retention should be reached for gas production wells in the Shenhu area of the northern South China Sea. A theoretical method was introduced to optimize the gravel packing operations in NGH production wells.\(^32\,33\) However, this method considers preventing coarse sand rather than striking a balance between plugging and sand retention. Hence, we proposed a balancing method\(^34\) to tackle issues faced with gravel packing sand control method. However, the selection of a proper aperture or slot size for standalone screen completion remains unclear. Further, all these methods relating to gravel packing completion rarely consider the longitudinal nonuniformity of PSDs.

This paper proposes a screen sand control protocol called holding coarse expelling fine particles (HCEFP). The protocol provides a new optimization method for the sizing of screen mesh for clayey silt hydrate reservoirs, which are widely spread in the northern South China Sea. A case study will be described based on the drilling results from the Site W18, which is located in the Shenhu area of the northern South China Sea. This study provides guidelines for the design of layered sand control optimization with respect to screen well completion and details on the engineering control of sand production from clayey silt GHBS, which is the main type of oceanic gas hydrate reservoirs.

2 | HCEFP SAND CONTROL PROTOCOL

2.1 | Proposal of the HCEFP method

Poor sand-retention performance of sand control completion reduces the skin effect, hence, enhances gas productivity. However, poor sand retention could also yield massive sand production. The result can be the erosion of wellbore and surface facilities and frequent wellbore interventions. Tight sand retention (eg, by using narrow aperture) reduces sanding, but increases plugging potential, hence, lower wellbore productivity. A proper sizing strategy should satisfy these contradicting requirements to mitigate both sanding and plugging.

The majority of the existing sand screen sizing methods are based on the sand bridging assumption and are related to the sorting coefficient of the formation sand.\(^34\) The main objectives in screen mesh sizing for hydrate production wells in
clay-rich sediment are as follows: (a) filter the relatively coarse sand particles to prolong the stability of sand-bridge and (b) allow the production of fine silts and clay to avoid the formation of mud cakes (Figure 1). Here, we call this method as holding coarse and expelling fine particles (HCEFP) method.

2.2 Screen sizing method

2.2.1 Analysis and division of formation particles

Figure 2 presents a flowchart for screen sizing using the HCEFP method. The PSD characteristics are the bases for down-hole sand control optimization. The first step in HCEFP method is to analyze the original PSD characteristics to obtain the uniformity coefficient, as well as intrinsic values, such as the median grain diameter. Additionally, clay composition and content should be determined.

The uniformity coefficient reflects the overall distribution range of the formation sand, while the sorting coefficient describes the distribution of grain sizes. Equations (1) and (2), respectively, define the sorting and uniformity coefficients where $F$ and $C$ represent the dimensionless homogeneity and uniformity coefficients, respectively. The parameter $\phi$ is equivalent to $(-\log d_i)$, in which $d_i$ is the sand diameter in millimeter, and the subscripts for $d$ and $\phi$ are the accumulative mass percentage for the sand whose diameter is larger than $d$.

The sand and silt content should be divided into relatively fine and coarse particles. The fine silt particles should be allowed to pass through the sand control media. Therefore, the candidate screen size should be avoided to allow the fine particles to pass through the sand control screen. Additionally, a sand-bridge tends to form easily when the particle diameters exceed one-third of the critical boundary diameter. It should be noted that the critical boundary diameter between the relatively fine particles and relatively coarse particles is different for different formation sediments. In other words, the sizes of coarse and fine particles are relative values in the HCEFP method, which differs from absolute grain-size definitions in sedimentology.

2.2.2 Screen size optimization

The subcomponent with diameters that are smaller than the critical boundary diameter should be allowed to pass through the sand control media. Thus, the critical boundary diameter is the baseline to select the smallest mesh size to expel the relatively fine particles. Meanwhile, a sand-bridge tends to form easily when the particle diameters exceed one-third of the screen aperture. Therefore, the candidate screen size should meet the preconditions defined in Equation (4), where $W_i$ represents the screen aperture size required to expel the relatively fine particles, and $d_i$ is the value of the critical boundary diameter between the relatively fine particles and the relatively coarse particles.

Next, the relatively coarse particles will be considered independently to select the proper screen aperture size. The uniformity and sorting coefficients, as well as the median grain diameter of the relatively coarse subcomponent, are calculated based on PSD characteristics of the relatively coarse subcomponent. Then, conventional screen sizing methods used by the petroleum industry are used to calculate the
One of the classic and most popular methods is illustrated in Equation (5).

\[ W_2 = d_{50} \]  \hspace{1cm} (5)

where \( W_2 \) represents the maximum screen aperture size required to hold the relatively coarse particles (μm), and \( d_{50} \) is the median grain diameter of the relatively coarse subcomponent (μm).
Recently, a novel method was developed by taking into account productivity and well completion requirements.\textsuperscript{38} This method can be adapted to retain the relatively coarse subcomponent in hydrate production wells, shown in Equation (6).

\[ W_2 = 0.333d_{50} + 0.387d_{70} + 0.510d_{90} \ (C')^{0.1511} \quad (6) \]

where \( d_{70} \) and \( d_{90} \) represent the diameters with accumulative weight percentages of 70\% and 90\% in the relatively coarse subcomponent, respectively (\( \mu m \)); \( C' \) represents the dimensionless uniformity coefficient of the relatively coarse subcomponent.

Therefore, the candidate screen aperture size to expel the relatively fine particles can be viewed as a semi-infinite interval defined by Equation (7), whereas the proper screen aperture size to retain the relatively coarse particles is obtained from Equation (8).

\[ A = [W_1, + \infty) \quad (7) \]
\[ B = (0, W_2] \quad (8) \]

where \( A \) and \( B \) are mathematical aggregations for the relatively fine subcomponent and the relatively coarse sand, respectively.

The intersection of the mathematical aggregations of \( A \) and \( B \) can be used as the candidate screen size for gas production wells in GHBS, which is described in Equation (9).

\[ W_{\text{sand}} \in C = A \cap B \quad (9) \]

where \( W_{\text{sand}} \) is the optimized screen size for clayey silt hydrate production wells (\( \mu m \)).

The above screen mesh size optimization method can be easily extended to global screen mesh size optimization for all production intervals, provided that we can obtain the original PSDs along the production intervals. As a case study for Site W18, the following sections will focus on the optimization of both the screen sizing and multi-stage layering of all production intervals.

3 | SAND CONTROL PARAMETER OPTIMIZATION FOR THE SITE W18

3.1 | Geological settings

Site W18 is in the Shenhu gas hydrate zone located in the central part of the north slope in the South China Sea\textsuperscript{39,40} and is part of the Baiyun Sag (Figure 3). The Shenhu hydrate zone is a well-surveyed area in China. Both the first (2007) and third (2015) Chinese national hydrate expeditions recovered hydrate samples from this area.\textsuperscript{41} China’s first marine hydrate production trial was also conducted in this area.\textsuperscript{42} Laboratory core tests show that the GHBS in the Shenhu area is rich in clay minerals,\textsuperscript{33} with a small portion of calcareous microfossils and planktonic foraminifera. By lithology, the hydrate-bearing sediment is classified as clayey silt fine sand.

The average water depth at Site W18 is 1272 m. Gas hydrate is unevenly distributed along the interval from 133 to 162 mbsf, with a hydrate saturation of up to \( \sim 64\% \). Gas composition analyses indicate that methane dominates the hydrate-bound gas (up to 99.5\%) and isotope tests reveal that the gas is mainly thermogenic.\textsuperscript{44}

3.2 | Original PSD characteristics

The hydrate-bearing samples obtained from different depths at Site W18 were analyzed. Figure 4 shows the typical PSD curves for six samples. Sediment at Site W18 is mainly composed of fine grain particles (\( \sim 63 \, \mu m, >88\% \)), with a small portion of sand (63-500 \( \mu m, <10\% \)) and coarse sand (>500 \( \mu m, <2\% \)). Mean grain sizes of the samples range from 14.5 \( \mu m \) to 35 \( \mu m \), with severe PSD heterogeneity along the hydrate-bearing interval.

Moreover, mineral composition tests indicate extremely high clay content (24.6\%-35.1\%), in which montmorillonite (36.25\%-40.75\%) and illite (29.00\%-34.75\%) are dominant. These clay minerals, especially montmorillonite, can easily trigger screen media blockage and increase the skin effect. Thus, the high clay mineral content in the GHBS will seriously affect the pressure transmission efficiency between the formation and borehole. Anticlogging characteristics for the sand control screen are important considerations for screen size optimization at Site W18.

Tables 1 and 2 list the sorting and homogeneity characteristics of the formation materials at Site W18. It can be seen from Table 1 that the sorting coefficient from the sedimentological formula is slightly higher than that obtained from Berg’s equation. The GHBS particles at Site W18 can be classified as severely distributed sand with bad sorting properties. Both the poor sorting and elevated uniformity coefficients pose significant challenges to sand control screen size optimization.

The PSD characteristics at Site W18 are a typical example of GHBS in the Shenhu area. During depressurization, we encounter two challenges associated with the sand control operation for clayey silt GHBS. Firstly, bad sorting and severely distributed characteristics render full-size sand retention via mechanical sand control media impossible. Further, PSDs longitudinal heterogeneity poses a difficulty to use a single screen size to meet the requirement of the entire production interval in hydrate production wells. A multi-stage sand control optimization method is crucial. The following sections will try to tackle these challenges by adopting the HCEFP method.
3.3 | Particle size division

Equation (3) was introduced to alter the mass-fraction-based PSD curve into particle-number-based PSD curve. Figure 5 shows the semi-log relationship between particle number and particle diameter for a core sample at 1436 m. It is indicated in Figure 5 that the critical boundary diameter between the relatively fine and coarse particles is 10 μm.

The \( d_{i} \)-log \( N_{i} \) relationships for all coring samples can be obtained using the same procedures depicted in Figure 5. Figure
Figure 6 shows the distribution of the critical boundary diameter along the production interval. We observe from Figure 6 that the critical boundary diameters range between 8.5 and 13.2 μm within the hydrate production interval. The longitudinal heterogeneity distribution characteristics of the critical boundary diameters demonstrate the necessity of multi-stage sand control operation.

3.4 | PSD analysis of the relatively coarse particles

Figures 7 and 8 illustrate the PSD curves and relevant sorting coefficients and uniformity coefficients of the whole PSD as well as the relatively coarse particles. Figure 7 indicates that mean grain sizes of the relatively coarse particles range from 31 to 73 μm. Also, the sorting and uniformity coefficients are 1.35-1.74 and 3.09-4.26, respectively (Figure 8). Comparing these values with the evaluation criteria showed in Tables 1 and 2, we found that the relatively coarse particles can be defined as uniform and well-sorted sand, which would benefit effectiveness of sand control operation.

If the relatively fine particles are removed from the original formation sediments, the sediment uniformity coefficient will be decreased to 3.09 or even less and the sorting coefficient will be decreased to lower than 1.74. The sorting coefficient in Figure 8B was calculated using Berg’s Equation. The decrease in both the uniformity and sorting coefficients will locally benefit sand retention along the entire production interval. Longitudinal statistical variation in the sediment along the production interval can be characterized by the standard
FIGURE 7  Typical particle size distribution (PSD) curves for coarse sand at the site W18

![Typical particle size distribution (PSD) curves for coarse sand at the site W18](image)

FIGURE 8  Uniformity and sorting coefficients in the whole particle size distribution (PSD) and relatively coarse particles

![Uniformity and sorting coefficients in the whole particle size distribution (PSD) and relatively coarse particles](image)

deviation associated with the uniformity and sorting coefficients, which are defined in Equations (10) and (11).

\[
\sigma_F = \sqrt{\frac{\sum_{i=1}^{N} (F_i - \overline{F})^2}{N}}, \quad \overline{F} = \frac{1}{N} \sum_{i=1}^{N} F_i \tag{10}
\]

| TABLE 3 | Particle size distribution (PSD) longitudinal standard deviation assessment results for Site W18 |
|----------|---------------------------------------------------|
|          | Original PSD | Coarse component |
| Sorting coefficient | 0.28  | 0.13  |
| Uniformity coefficient | 4.26  | 0.28  |
where $\sigma_F$ and $\sigma_c$ are the standard deviation of the sorting and uniformity coefficients, respectively, $\bar{F}$ and $\bar{C}$ are the average sorting and uniformity coefficients, and $N$ represents the number of samples used for PSD analysis.

Equations (10) and (11) and Figure 8 can be used to predict the standard deviation for the uniformity and sorting coefficients for both the original PSDs and relatively coarse particles. Table 3 lists the standard deviation results. Results indicate that removing relatively fine particles may decrease longitudinal heterogeneity in the sediment. The outcome is the lower number of divided sublayers for the multi-stage sand control operation.

### 3.5 Screen sizing

Based on the HCEFP method described in the previous section, we can obtain both $W_1$ and $W_2$ for each sediment sample from different depths (Figure 9). In Figure 9A, $W_2$ is calculated using Equation (3), while the same in Figure 8B is obtained from Equation (4). The screen aperture sizes located between $W_1$ and $W_2$ are thought to be suitable for holding coarse particle, as well as expelling fine particles. Figure 9 indicates variable suitable aperture sizes for different depths due to the longitudinal heterogeneity.

### 3.6 Multistage sand control design

Figure 9 shows the variable optimal aperture size along the production interval. Hence, sand control screen with different aperture sizes should be installed at various depths along the production interval. However, using screens with variable design in the wellbore is difficult and costly. Therefore, the number of design variations should be minimized per procedure outlined herein and demonstrated by a case study using the data in Figure 9A.

The design process begins from the bottom of the production interval. Either the deepest $W_1$ or $W_2$ values in Figure 9 can be used as the starting point. We draw a vertical line at the local minimum $W_2$ and another vertical line at the local maximum $W_1$ for the lowest interval. In Figure 9, we start from Point A and draw a vertical line that intersects the $W_1$ curve (point B) to form the line $\overline{AB}$. The line $\overline{AB}$ corresponds to the lower-bound aperture size for this interval. Within the interval determined by point A and B, we can obtain the line $\overline{CD}$ which corresponds to the maximum screen mesh size required for this interval.

This procedure is repeated at upper intervals until reaching the top of the production interval. This procedure allows for obtaining suitable sand control design for the whole wellbore.

The width of the aperture window for these intervals dictates the length of each interval. A wider window provides a superior sanding performance and some flexibility to tolerate...
some plugging. However, a wider window also requires a higher design variation, which is not desirable.

Based on the above steps, Table 4 lists several recommendations for candidate sublayer division and the corresponding screen mesh size for Site W18. Based on Figure 9A and Table 4, we recommend that the entire production interval should be divided into two subintervals. However, Figure 9B indicates three subintervals division.

To simplify difficulties associated with the operation, the production interval should be divided into two subintervals, which correspond to the lower subinterval, located deeper than 1434 m, and the upper subinterval, located between 1400 and 1434 m. The recommended screen mesh sizes for the lower subinterval are 30-35 μm while that for the upper subinterval are 40-45 μm.

4 | CONCLUSIONS

Sand control during gas recovery from clayey silt hydrate reservoirs has been a challenge for the industry and academia for a long time. This study presented a screen design protocol called HCEFP and performed a preliminary analysis of sand control optimization for clayey silt hydrate production wells. Both the local aperture size selection and full-interval multistage sand control design method were presented based on the geological data from Site W18 in the Shenhu area of the northern South China Sea. This study yields the following results and conclusions.

1. There are two main challenges concerning the sand control during depressurization of clayey silt GHBS. Firstly, complete solid retention via a standalone screen is rarely beneficial as high clay contents can adversely affect wellbore gas productivity due to excessive plugging. Moreover, longitudinal heterogeneity of the PSDs increases the difficulties associated with sand control design. Therefore, screen aperture size selection for clayey silt hydrate wells should strike a balance between retaining coarser particles and avoiding screen blockage by the relatively fine particles. Multistage sand control optimization is strongly recommended in clayey silt hydrate production wells.

2. The GHBS in the Shenhu Area of the northern South China Sea is classified as clayey silt sediment. Mean grain sizes of the samples at the site W18 range from 14.5 μm to 35 μm, with significant longitudinal PSD heterogeneity along the hydrate-bearing interval. The GHBS is rich in clay (24.6%-35.1%). Both the sorting and uniformity coefficients of the samples are high. As an example for HCEFP protocol, we recommend that the entire production interval of the W18 site should be divided into two subintervals for multi-stage sand control operation. The candidate screen mesh size for the lower subinterval (deeper than 1434 m) is 30-35 μm and that for the upper subinterval (shallower than 1434 m) is 40-45 μm.

3. Since the HCEFP protocol allows the flow of fine particles and clay into the borehole during the early stages of depressurization, the sand control operation should be supplemented with appropriate sand transport in the wellbore. Ultimately, the effectiveness of the HCEFP protocol in clayey silt hydrate production wells relies on its field tests. Future verifications are ongoing and will be discussed in future studies.

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