Effect of thickness ratio of overlaying layer to hydrate bearing stratum upon the settlement of seabed sediments during Natural Gas Hydrate Dissociation

Hongbo Li, Shuzhi Ma*

Engineering Faculty, China University of Geosciences, Wu Han, Hubei,430074,China

*Corresponding author’s e-mail:maszyy@163.com

Abstract. The dissociation of natural gas hydrate in the process of exploitation will weaken the mechanical properties of the surrounding soil, which will lead to the deformation and destruction of the seabed sediment, thus posing a potential threat to the safety of the undersea engineering infrastructures. In this paper, the finite difference method is used to simulate the vertical deformation of seabed sediments, and examine the effect of thickness ratio of the overlying layer to the HBS upon soil settlement via an established three-dimensional model of submarine hydrate mining. The main research results are as follows: The maximum settlement occurred at the top surface of HBS dissociation centre and the settlement decreased significantly from the mining well to the surrounding and from HBS to the overlying layer. The range of settlement trough on the top of HBS is far less than the overlaying layers. The thickness ratio of the overlying layer to the HBS will have a great influence on the distribution of sedimentation and deformation of seafloor sediments caused by hydrate dissociation. The deformation and the range of the settlement trough both decrease with the increasing thickness ratio of overlying layer to HBS. The research results will provide a strong theoretical reference for the stability of seabed and mining platform during hydrate mining.

1. Introduction

Natural gas hydrate is a clean energy characterized by huge mining potential, and is widely distributed in submarine continental shelves, submarine slopes, and permafrost regions. Five main methods for extracting hydrates were proposed including depressurization, thermal stimulation, inhibitor injection, carbon dioxide replacement and solid fluidization [1]. However, no matter which extraction method is used, such mining process always involve the decomposition of hydrates, the transformation of solid hydrates to water and natural gas. The solid hydrates can act as a rock and soil skeleton and cementation to increase the strength of hydrate bearing stratum (HBS). When hydrates decompose, such effects are weakened or even disappeared, which will cause HBS to soften and its strength reduced, resulting in deformation and settlement of HBS and its over layers, further inducing possible geological disasters such as seabed landslide and wellbore instability, threatening the safety of subsea engineering infrastructure [2-5].

Due to the increasing demand of energy around the world, the exploitation of natural gas hydrate has attracted considerable research efforts, and the deformation of seabed sediment caused by hydrate dissociation is also one of the hot fields of geological engineering research. But one thing that needs to be point out is that most of previous studies used numerical simulation to focus on the effects of different factors like mining methods, formation dip angles and hydrate dissociation ranges on seabed
deformation [2-7]. Few studies on the deformation characteristics of sedimentary strata under different thickness of soil layers and HBS combination structure have been reported.

In fact, with the development of hydrate exploitation, the deformation and distribution characteristics of soil layer is also closely related to the combined structural characteristics of HBS and upper and lower soil layers. Obviously, the larger the reservoir thickness and the thinner the overlying layer, the more serious the deformation caused by hydrate mining, while the thinner the reservoir thickness and the thicker the overlying layer, the less serious the deformation caused by hydrate mining. The thickness ratio of the overlying layer to the HBS will have a great influence on the distribution of sedimentation and deformation of seafloor sediments caused by hydrate dissociation. Therefore, the research on the influence of the thickness ratio of the overlying layer to the HBS on the stratum settlement in hydrate mining is of great practical significance.

In this paper, the finite difference method is used to simulate the settlement of sediments after hydrates dissociation to investigate the regularity distribution of settlements, and the influence of thickness ratio of overburden on the settlement distribution characteristics.

2. Numerical Simulation

2.1 Geological and numerical model

The reported drilling data of the Shenhu sea area in the South China Sea show that main hydrate layers are mainly distributed in the range of 100–200 m below the seabed, and their thickness are generally 10–80 m [8–10].

Considering most of the stratigraphic distribution, the geological model in this paper is simplified to three soil layers, from top to bottom: the overlying layer is clayey silt, 140–170 m; the hydrate bearing stratum(HBS) is clayey silt, 20 m; the lower layer is clayey silt, 100m. Slope of seafloor soil layer is considered to be horizontal and depth of water is taken as 800 m. And there is a mining well located at center of the geological model. Sketch of geological section is shown in Figure 1.

![Figure 1. Sketch of geological section.](image)

In order to decrease the boundary effects, the length and width of numerical model are selected to be 400 m. Considering the impact on hydrates when the production well is working[11], the hydrate dissociation range is defined as a cylindrical shape with a radius of 20 m in the center of the production well. The zone within 20 m around the production well is subdivided more detailed to improve the accuracy of numerical calculation. Mining well simulated by unit pile has an inner diameter of 20 cm and a wall thickness of 2 cm, which is drilled to the top surface of the lower layer. A contact surface is set between the outer surface of well and sediments, which allows relative slip on tangential direction. Boundary constraints of the model are as follows: the top surface of the model is free, the bottom boundary and the surrounding boundaries are all constraint in normal direction. Sketch of numerical model is shown in Figure 2.
Figure 2. Sketch of numerical model
This work is focusing on the seafloor subsidence of the overlying layer and the hydrate bearing stratum upon hydrates dissociation under different thickness ratio of the overlying layer to HBS. In this paper, the influences of the thickness ratio on deformation of seafloor sediments is investigated in four working conditions, as shown in Table 1.

Table 1. Four conditions of different thickness ratio.

| Con. | Thickness of overlying layer(m) | Thickness of HBS(m) | Thickness of lower layer(m) | Thickness ratio |
|------|--------------------------------|--------------------|-----------------------------|----------------|
| Con. I | 140                           | 20                 | 100                         | 7              |
| Con. II | 150                          | 20                 | 100                         | 7.5            |
| Con. III | 160                          | 20                 | 100                         | 8              |
| Con. IV | 170                          | 20                 | 100                         | 8.5            |

2.2 Constitutive model and parameters of soil and structure
Like many references, Mohr-Column constitutive relation is used in soil, elastic constitutive relation is used in well, column shear constitutive relation is used in contact element. By synthesizing the datum in some literature [12-14], the physical and mechanical parameters of HBS before and after dissociation, overlying layer, lower layer and wall are shown in Table 2, and the parameters of contact surface are shown in Table 3.

Table 2. Physical and mechanical parameters of soil and well.

| Material            | Density $\rho$(kg/m$^3$) | Modulus $E$(MPa) | Poisson’s ratio $\mu$ | Cohesion $C$(kPa) | Friction angle $\phi$(°) |
|---------------------|---------------------------|-------------------|-----------------------|--------------------|---------------------|
| Overlying layer     | 1960                      | 27                | 0.36                  | 15                 | 9.3                 |
| HBS(no dissociation)| 1972                      | 96                | 0.32                  | 158                | 10                  |
| HBS(after dissociation) | 1962                  | 20                | 0.36                  | 5                  | 9                   |
| Lower layer         | 1970                      | 38                | 0.31                  | 32                 | 11.6                |
| Well                | 7800                      | 26E3              | 0.18                  | --                 | --                  |

Table 3. Parameters of interface.

| Material | Cohesion $C$(kPa) | Friction angle $\phi$(°) | Normal stiffness $kn$(MPa) | Tangential stiffness $ks$(MPa) |
|----------|-------------------|--------------------------|---------------------------|-------------------------------|
| Interface| 0                 | 1.5                      | 2000                      | 2000                          |
3. Results and discussion

3.1 Spatial distribution characteristics of vertical displacement

To clarify the spatial distribution characteristics of the vertical displacement field of overlying soil and HBS upon hydrate dissociation, we employ the simulation results under the overlying layer and HBS thickness ratio of 7.5 (condition II in Table 1) for analysis.

Figure 3. Settlement contour of vertical section under Con. II.

Figure 3 is the settlement contour of vertical section across the mining well centroid. It is clear that the obvious settlement can be observed, and the biggest settlement occurred at the top surface of HBS dissociation center and the settlement decreased significantly from the mining well to the surrounding and from HBS to the overlying layer. The rebound occurred at the bottom of HBS is also similar to the settlement distribution: at the center of HBS bottom surface shows the maximum rebound, and it decreases significantly as the stress change transmits either beyond the center or downward to the lower layer.

Figure 4. Settlement of different positions in simulated model under Con. II.

For detailed analysis of the settlement trend, Figure 4 give the curves of settlement with respect to the distance from the mining well of overlying layer top surface (cubic model surface) and HBS top surface. It can be seen either Figure 4(a) or Figure 4(b) exhibits a parabolic shape of settlement with the greatest value centered in the well and decreased gradually to both sides, the opening of such parabolic curves indicates the relatively violent influence range of hydrate dissociation, which can be called a dish settlement trough.

The radius of such settlement trough in Figure 4(a) is of around 125 m, 6.25 times as big as the hydrate dissociation range (20 m), whilst the center settlement is rather small, around 9.06 cm, just 0.45% of the thickness of HBS (20 m). Similarly, the top surface of HBS exhibits the greatest centroid settlement of 95.15 cm (Figure 4(b)), 4.75% of HBS thickness, and settlement trough with radius of around 30 m, 1.5 times of the hydrate mining range. Beyond the impact trough range of subsidence, settlement of the overlying layer and the HBS are gradually stable at about 4.72 cm and 0.48 cm, respectively.
Comparing the settlement from Figure 4(a) and Figure 4(b), one can rationally infer that the settlement increases as the seafloor depth increases, while influence area shrinks. This is because the stress change caused by reduction in strength during hydrate dissociation is gradually attenuated when it transmits upward. Such shapes of settlement curves are consistent with intuition indicating the simulation results are reliable.

Nevertheless, the simulation results in Figure 3 and Figure 4 indicate the vertical settlement deformation occurs due to the softening of HBS upon the hydrate dissociation. Such settlement gives the subsidence trough in the overlying layer and the HBS concentrated in a circular area with a certain radius. The affected area subject to settlement for overlying layer is greater than that for HBS. The above spatial distribution settlement also suggest specific requirement to the deformation ability for submarine infrastructure located in the (near) center of hydrate mining, as the settlement there is greater than that beyond the mining center, resultantly, the materials with high strength and high tolerance for deformation are required to enhance the structure stability.

3.2 Calculation results under different thickness ratio

When mining hydrates in different areas, there are different thickness ratio of the overlying layer to the HBS, and the thickness ratio will have a greater impact on the settlement distribution of surrounding soil during hydrate dissociation.

Figure 5. Settlement under different thickness ratios

Figure 5(a) presents settlement of overlying layer different thickness ratios. The exhibited settlement curves take on parabolic shape of subsidence trough. At thickness ratio of 8.5 and 8 (the thickness of the overlying layer 160 m and 170 m, respectively), the settlement amount of the overlying layer is about 0.25 and 2.13 cm, respectively, and the curve variation is rather gentle. When thickness ratio decreased to 7.5 (the thickness of the overlying layer is 150 m), the settlement of the overlying layer obviously increased and the settlement curve forms a settlement groove around the mining center with maximum settlement around 9.07 cm. When the curve spreads to both sides, the settlement decreases and tends to be flat until it spreads to about 125 m from mining center with an essentially constant settlement about 5.52 cm. As thickness ratio further decreased to 7 (thickness of the overlying layer is 140 m), the settlement increased with a centered maximum value of 18.48 and the influence range of about 125 m from the mining center. The HBS settlement curves in Figure 5(b) showed similar shape to those in Figure 5(a), but with much higher maximum settlement in the centered mining well. As the thickness ratio increased from 7 to 7.5 (thickness of the overlying layer is 140 m and 150 m, respectively), the maximum settlement reduces from 128.36 cm to 95.15 cm. When the thickness ratio further increased 8 and 8.5, the maximum settlement decreased to 72.49 cm and 63.47 cm, respectively. Besides, the settlement trough of HBS top surface is much narrower compared to that of top overlying layer (Figure 5(a)), the HBS exhibited influence range limited in less than 45 m radius.
Since the mining infrastructures are directly built on the overlying top layer, its settlement is of particular concern for the design and building of such infrastructures. So, we re-plotted the maximum settlement and radius of influence area of overlying top layer with respect thickness ratios to make the observation more apparent, as shown in Figure 6. Below the thickness ratio of 8.0, the settlement is almost nearly inversely linear with the thickness ratio. Beyond the thickness ratio of 8.0, the settlement decrease is rather small. Also, the influence range also exhibited a linear decrease under thickness ratio of 8.0, and a slower decrease from thickness ratio of 8.0 to 8.5. Above observations indicate that the settlement of the overlying layer increases as the thickness ratio decreases, and the influence range also increases, also implying the thinner the overlying layer is, the more severe the settlement will be. This result is not only consistent the soil mechanics intuition, but remind that, for different mining areas with thin thickness of overlying layer, measures to control subsidence of sediments within the allowable range are needed, say, the thickness ratio less than 7.5.

4. Conclusions
The subsidence settlement of hydrate dissociation and the influence of thickness ratio on settlement distribution are studied in this paper. Main conclusions are as follows:

(1) During hydrate dissociation, the maximum settlement occurred at the top surface of HBS dissociation center and the settlement decreased significantly from the mining well to the surrounding and from HBS to the overlying layer, the maximum settlement of the HBS is 6~10 times larger than the overlying layer.

(2) As the thickness ratio of the overlying layer to the HBS increases, settlement of the overlying layer and the HBS both decreases. Particularly, when thickness ratio is no greater than 7.5, settlement of the overlying layer and the HBS will reach the danger value which may pose a threat to the mining stability.

(3) The relatively violent influence range of hydrate dissociation at different horizontal sections is dish-shaped settlement trough, the settlement trough on the top of HBS is narrower than that of overlaying layer, and the opening is relatively limited to the top of the overburden, which indicates that the relatively severe fan enclosure is far less than the overlaying layers.

Acknowledgments
This study was supported by the National Key Technologies R&D Program of China (No. 2017YFC0307700). Additional funding provided by the National Natural Science Foundation of China (No. 41672309). Authors are grateful to Xingwei Ren for his help and fantastic discussions.

References
[1] Jin, G., Xu, T., Xin, X., Wei, M. and Liu, C. (2016). Numerical evaluation of the methane production from unconfined gas hydrate-bearing sediment by thermal stimulation and
depressurization in Shenhu area, South China Sea. Journal of Natural Gas Science and Engineering, 33: 497-508.

[2] Brown, H.E., Holbrook, W.S., Hornbach, M.J. and Nealon, J. (2006). Slide structure and role of gas hydrate at the northern boundary of the Storegga Slide, offshore Norway. Marine Geology, 229(3-4):179-186.

[3] Kim, Y.G., Lee, S.M., Jin, Y.K., Baranov, B., Obzhirov, A., Salomatin, A. and Shoji, H. (2013). The stability of gas hydrate field in the northeastern continental slope of Sakhalin Island, Sea of Okhotsk, as inferred from analysis of heat flow data and its implications for slope failures. Marine and Petroleum Geology, 45:198-207.

[4] Song, B., Cheng, Y., Yan, C., Lyu, Y., Wei, J., Ding, J. and Li, Y. (2019). Seafloor subsidence response and submarine slope stability evaluation in response to hydrate dissociation. Journal of Natural Gas Science and Engineering, 65:197-211.

[5] Wang, S., Wang, L., Lu, X., Li, Q. (2008). Numerical Analysis of the Effects of Gas Hydrate Dissociation on the Stability of Deposits and Pipes. China Offshore Oil and Gas, 20: 127-131. [In Chinese]

[6] Lu, L., Zhang, X.H. and Lu, X.B. (2016). Numerical study on the stratum’s responses due to natural gas hydrate dissociation. Ships and Offshore Structures, 12(6):775-780.

[7] Zhao, Z., Shang, X. (2010). Numeric Simulation for the Seabed Deformation in the Process of Gas Hydrate Dissociated by Depressurization. Communications in Computer and Information Science, v 105 CCIS, n PART 1:296-303.

[8] Sun, J., Zhang, L., Ning, F., Lei, H., Liu, T., Hu, G., Lu, H., Lu, J., Liu, C., Jiang, G., Liang, J. and Wu, N. (2017). Production potential and stability of hydrate-bearing sediments at the site GMGS3-W19 in the South China Sea: A preliminary feasibility study. Marine and Petroleum Geology, 86: 447-473.

[9] Li, G., Moridis, G.J., Zhang, K. and Li, X. (2010). Evaluation of gas production potential from marine gas hydrate deposits in Shenhu area of South China Sea. Energy & Fuels, 24(11): 6018-6033.

[10] Yang, S., Liang, J., Lu, J., Qu, C., Liu, B. (2017). New understanding on accumulation characteristics and main controlling factors of natural gas hydrate in Shenhu sea area in the northern South China Sea. Earth Science Frontiers, 24(4):1-14. [In Chinese]

[11] Wang, J., Zhang, X., Lu, X., Shi, Y. (2017). Deformation of soil around the wellbore caused by gas hydrate dissociation. Journal of Water Resources and Architectural Engineering,15(6): 48-51. [In Chinese]

[12] Shi, Y., Zhang, X., Lu, X., Wang, S., Wang, A. (2015). Experimental study on the static mechanical properties of hydrate-bearing silty-clay in the South China Sea. Chinese Journal of Theoretical and Applied Mechanics, 47(3): 521-528. [In Chinese]

[13] Sun, Z. (2013). Experimental study on hydrate saturation and mechanical properties of gas hydrate-bearing sediments. China University of Petroleum PhD Essay. [In Chinese]

[14] Lu, B., Li, G., Zhang, F., Huang, S. (2005). Elastic properties of seafloor sediments in Southern South China Sea and their distributions. Journal of Tropical Oceanography. 24(3): 48-54. [In Chinese]