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Geomechanical issues in the exploitation of natural gas hydrate

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ABSTRACT: As a clean fossil fuel with great reserves, natural gas hydrate (NGH) is widely regarded as an important future alternative energy source. NGH is widely distributed in onshore tundra and shallow sedimentary layers in the deep sea. These sedimentary layers typically exits shallow burial depth, poor diagenesis and low strength characteristics; moreover, the decomposition of NGH can also greatly reduce reservoir strength. Therefore, NGH development can easily causes many geomechanical problems, including reservoir instability, sand production and seabed landslides, etc., which may further trigger a series of environmental disasters such as tsunamis, natural gas leakage and the acceleration of global warming. This study mainly reviews the research progress regarding geomechanical issues in NGH development, including mechanical properties of NGH-bearing sediments, borehole stability, hydraulic fracturing, sand production, reservoir settlement and seabed landslides. In addition to previous research achievements regarding geomechanical problems in NGH exploitation, the limitations and challenges are also discussed, and several questions and insightful suggestions are put forward for future research from our point of view.

Keywords: natural gas hydrate; geomechanical issues; borehole stability, hydraulic fracturing, sand production, seabed landslides

1 Introduction

With rapid economic and social development, the demand for energy has witnessed sustainable growth and the exploitation of conventional fossil fuels encountered a bottleneck; meanwhile, scholars are paying more attention on unconventional energy such as natural gas hydrate (NGH). NGH is a type of ice-like compound formed by the combination of water and gas molecules at low-temperature, high-pressure conditions (Sloan Jr and Koh, 2007). In the natural world, because of large reserves and its high energy density, NGH is regarded as one of the most important alternative energy sources in the 21st century and now attracts widespread attention from the scholars all over the world (Chong et al., 2016; Makogon et al., 2007;Nair et al., 2016). Approximately 1,500 billion tons carbon is stored in NGH, which occupies estimated 25% of mobile organic carbon in global land-ocean-atmosphere systems (Beaudoin et al., 2014), almost twice that of proven conventional mineral fuels such as coal, oil and natural gas (Kvenvolden, 1998; Yan et al., 2017). Because the massive amount of NGH on the seafloor has been found through deep sea drilling (Huene et al., 1980; Moore et al., 1982), many countries have successively formulated research and development plans of NGH, with the ultimate aim of achieving commercial development of NGH (Dickens, 2004; China Geological Survey Bureau, 2017; JOGMEC, 2017; Chen et al., 2018; Wu and Wang, 2018).

Because of limitations in phase equilibrium conditions and the geothermal gradient, NGH is mainly distributed in deep sea and permafrost areas (Chong et al., 2016) with shallow burial depth and poor cementing. NGH plays a strong cementing role in the reservoir (Yan et al., 2017), and the development of NGH can inevitably destroy cementing within the sediments and deteriorate the mechanical performances within the sedimentary layer (Hyodo et al., 2014). Meanwhile, a vast amount of water and gas can be released by the decomposition of NGH, which can lead to the increase of pore pressure in limited pore space and thus affect the stress field distribution (Cheng et al., 2013). Therefore, NGH development may also trigger geomechanical problems such as borehole instability, sand production, seabed settling and landslide (Hornbach et al., 2007; Liu et al., 2010; Cheng et al., 2013; Yan et al., 2018). Even more seriously, submarine landslide may also cause tsunamis and gas escape, thus exacerbating a series of disasters such as global warming (Hornbach et al., 2007; Chong et al., 2016). It can thus be concluded that NGH is also an important factor that affects submarine stability and the change of natural and environmental system in addition to a type of energy treasure (Dillon et al., 2001; Best et al., 2006; Lu, 2015).

Under the premise of ensuring environmental preservation and safety, solving geomechanical problems caused by NGH development, avoiding induced engineering and geological disasters and thus achieving safe and high-efficiency development of NGH resources will be a great challenge for science and engineering fields.

This review summarizes recent literature and improves the fundamental understanding of the geomechanical problems in NGH exploration and related effects on the environment. This study can provide an insightful reference for the selection of exploitation technology and identifying key weaknesses to be overcome.

2 Review of global NGH development

2.1 The status of production tests for NGH

NGH is widely distributed across the world (Fig. 1), and because of the great reserves and extremely high resource values, it has thus become a research hotspot in the energy industry. NGH content in seabed sediments is approximately more than 100 times greater than that of NGH in on-shore permafrost (Wang and Sun, 2018). Many countries, including America, Canada, Japan, India, China and Korea, have formulated long-term NGH development plans(Ruppel and Collett, 2013; Collett et al., 2014; Sun, 2018). It is estimated that gas hydrate will begin through small-scale commercial development and gradually become the main global natural gas supply sources during 2020 to 2030 (Ruppel, 2011) .

Currently, research on NGH development has taken a ‘one-land and three-sea’ pattern; to be specific, ‘one-land’ refers to west Siberian, Mackenzie in Canada and Alaska in USA, which are all located in the Arctic tundra, and ‘three-sea’ refers to the Gulf of Mexico, coastal zones in India, South China Sea and Japan Sea. Production tests of NGH reservoirs are also concentrated in above regions (shown in Table 1). Because NGH can only exist under specific temperature and pressure conditions, NGH can be exploited via heat injection method, depressurization method, chemical reagent injection method, CO_2 replacement method and solid fluidization (Grace et al., 2008; Konno et al., 2015; Lu et al., 2017; Oyama and Masutani, 2017; Zhou et al., 2017). The basic idea is to break the phase equilibrium via pressure drop or temperature rise or by injecting an inhibitor so as to promote the decomposition of NGH, and then collect the overflowing natural gas.

2.2 The challenges of NGH development

The production tests of NGH in many countries confirm that NGH can be exploited, which provide a great reference for future studies. However, NGH development also encounters many theoretical and technical challenges, and still has far to go before commercial exploitation. The following problems have been exposed during the production test process. Firstly, the productivity of a single well only has a reach of tens of thousand cubic meters of natural gas, which is far below the economic threshold of deepwater gas field development (hundreds of thousands of cubic meters). How to exploit different types of wells and adequately choose the development and completion method still needs further investigation. Secondly, several unique physical and mechanical properties of NGH-bearing sediments such as shallow burial depth and non-diagenesis lead to complex underground outbursts and a high risk of geological disasters. How to prevent or alleviate these underground risks is necessary for ensuring long-term, safe and high-efficiency NGH production. Therefore, interdisciplinary scholars should work jointly and explore novel disaster prevention and reduction technologies. Thirdly, deepwater oil and gas drilling ships are mainly used in current NGH production tests, which were designed for drilling and exploring oil and gas several thousand meters below the seabed. These ships have high construction cost and expensive daily operation. High-efficiency deep sea NGH exploitation requires proprietary equipment and tools in accordance with the shallow burial depth of NGH so as to reduce operational cost.

The solution to the above problems is related to the geomechanical properties of the hydrate sediments. Some geomechanical problems such as borehole stability, sediment stimulation, sand production, sediment settlement and submarine landslide are directly related to the safe and efficient mining of hydrates. The mechanical properties of the sediments form the basis for understanding these geomechanical problems. We will introduce the research progress in these aspects as the following.

3 Mechanical properties of NGH-bearing sediments

The occurrence of the engineering and geological disasters and the application of reservoir stimulation is closely related to the basic geomechanical properties of the reservoir. For avoiding the occurrence of engineering and geological disasters in production and achieving long-term safe and high-efficiency exploitation of NGH-bearing sediments, we need to accurately predict the mechanical properties of NGH-bearing sediments and reveal the deformation and failure mechanisms of NGH-bearing sediments in the drilling and production processes.

According to related theories in solid physicals, physical properties of crystals are heavily controlled by the crystal structure. In addition to the thermal conductivity coefficient, Young's modulus, bulk modulus, shear modulus and Poisson's ratio of pure NGH are quite close to the corresponding properties of ice (Table 2) (Kuustraa and Hammershaimb, 1983; Dvorkin et al., 2000; Waite et al., 2000).

3.1 In-situ formation and test on mechanical properties of NGH-bearing sediments

Because NGH can only exist in a low-temperature and high-pressure environment, NGH-bearing sediment cores should be acquired via pressure-retaining coring, which poses great technical difficulties and requires high operational costs. Moreover, NGH-bearing sediment cores can hardly be acquired in-situ. Therefore, there have been only a few mechanical experiments performed on NGH sample from real reservoirs (Winters et al., 2004; Masui et al., 2007; Winters et al., 2007;Masui et al., 2008; Miyazaki et al., 2010; Miyazaki et al., 2011; Hyodo et al., 2013). Normally, researchers mainly simulate seabed sediment rock samples in the laboratory through measuring mechanical properties of NGH-bearing sediments, and then in- situ synthesize NGH for mechanical properties testing.(Hyodo et al., 2002; Li et al., 2011; Li et al., 2012; Liu et al., 2016; Yan et al., 2017; Kajiyama et al., 2017; Zhang et al., 2018).

In order to make the physical and mechanical properties of the artificial sample as similar as actual reservoir possibly, hydrate in-situ formation is favored by researchers. Hydrate in-situ formation refers to inject natural gas into a water-bearing formation under simulated reservoir conditions to form natural gas hydrates in the rock sample and do mechanical testing directly. The hydrate in-situ formation can be realized by two methods: partial water saturation method and complete water saturation method. Partial water saturation method is to partially saturate the sediment sample with the amount of water required to generate the target saturation, and then inject enough methane gas for controlling the temperature and pressure of the sample to make the water form hydrated completely(Waite et al., 2003). The complete water saturation method requires to make the sample completely water-saturated, and then inject into the quantitative methane gas to form hydrate(Winters, 2002). Since the hydrate sample produced by the complete water saturation method is similar to the formation of hydrate deposits in the ocean, the sample obtained by this method is closer to the real situation.

The key purpose of hydrate in-situ formation is to provide experimental samples as close as possible to the actual situation. Since the in-situ formation of hydrates can change the various physical parameters of the sand body and change the temperature and pressure conditions inside the reactor, it is critical to ensure that the hydrates are similar to the actual formation properties after in-situ growth(Gupta et al., 2017). For example, the formation of the hydrate is an exothermic process, how to monitor and maintain the internal temperature of the reactor, especially the temperature control of the hydrate formation, is important. Monitoring of hydrate saturation is another experimental difficulty. The currently accepted method for determining hydrate saturation is based on the amount of gas or water, combined with the hydrate formation reaction formula to estimate the volume of formed hydrate, and further estimate the hydrate saturation. However, how much gas in the reactor involved in hydrate formation and the residual amount of gas still lack of an accurate determination.

Since hydrate formation must be carried out in a low temperature and high pressure environment, the traditional rock triaxial mechanical experiment cannot perform in-situ synthesis and mechanical property testing of hydrate reservoir samples. The researchers have improved it for testing the mechanical properties of hydrates. The earliest mechanical experiment device of NGH-bearing sediments was developed by the National Energy Technology Laboratory and the US Bureau of Geodetic Engineering, but it can only test the mechanical properties under small strain conditions(Winters et al., 2007). Then, Yamaguchi University, Nagasaki University and Japan Industrial Technology Research Institute, China's Qingdao Institute of Marine Geology, Dalian University of Technology, China University of Petroleum and other units have developed in-situ synthesis of hydrate and the triaxial test system to be able to carry out the in-situ growth and mechanical testing experiments of hydrates in sediments. In general, the experimental NGH mechanical properties measurement system consists of in-situ synthesis module, the triaxial test module of rock mechanics in low temperature, core preparation module and physical property measuring module(Aoki et al., 2004; Masayuki et al., 2005; Hyodo et al., 2007; Zhang et al., 2010;

Sun et al., 2011; Yoneda et al., 2011; Li et al., 2011;Liu et al., 2016; Liu et al., 2018). Recently, in order to study the failure mechanism of hydrate reservoirs well, researchers have begun to combine in-situ synthesis of hydrate and triaxial test system with CT testers, using CT scanning technology to achieve real-time monitoring of in-situ growth and reservoir microscopic structures changing in mechanical experiment. It provides a good example for the determination of hydrate saturation and spatial distribution in the in-situ hydrate synthesis experiment in the future.

Due to limitations in instruments and experimental technologies, several researchers have attempted to use tetrahydrofuran hydrate (Zhang et al., 2010) or ice (Winters et al., 2004; Winters et al., 2007) as substitutes for NGH-bearing sediments so as to investigate mechanical properties. However, tetrahydrofuran hydrate differs from NGH in formation pattern. Whether a prepared sample can truly reflect the strength and deformation characteristics of NGH-bearing sediments still needs further validation.

3.2 The influence factors on mechanical properties of NGH-bearing sediments

NGH exists in sediment particles in the form of cementing, pore filling and sediment skeleton (Sánchez et al., 2017). Using CT scanning during the formation progress of synthetic NGH in sediments (Fig. 2), NGH usually shows a mixed distribution pattern, and different distribution modes dominate in different formation phases of NGH. At low saturation, NGH mainly exists in cementing; as the saturation increases, NGH mainly exists in the fluid in the pores in a suspended pattern; with higher saturation of NGH, suspended NGH grows and aggregates slowly, which thus gradually fills in pores among particles. Finally, NGH acts together with the sediment as the force-bearing bodies.

NGH exists in different forms in pores, and imposes different effects on the sediment skeleton, thereby leading to different mechanical properties of the reservoirs. NGH as a cement, imposes the most remarkable effect on the mechanical characteristics of sediments. Generally, the cementing effect of NGH is positively correlated to its saturation (Hyodo et al., 2007; Masui et al., 2008; Li, 2013; Yoneda et al., 2017; Loret, 2019). The strength of NGH-bearing formation is determined by NGH strength, friction among particles and cementing among particles (Jiang and Zhu, 2014; Kajiyama et al., 2017). The existence of NGH cementing constraints relative motion of sediment particles under loading, which can thus enhance the overall strength and stiffness of the sediments. Accordingly, both strength and stiffness of sediments increase with the increasing NGH saturation. However, the properties of various NGH-bearing sediments with identical saturation may differ greatly because NGH exhibits different distribution patterns within the pores (Masui et al., 2005; Hyodo et al., 2007; Li et al., 2012). The strength of NGH particles is quite low compared to that of sediment particles, and therefore, the internal friction angle of NGH-bearing sediments are mainly determined by the frictional resistance produced by inlaying, occlusion and dislocation among sediment particles under pressure; the occlusal force between sediment and NGH particles imposes a slight effect. Therefore, the existence of NGH mainly affects the cohesion (Liu et al., 2018), although it slightly affects the internal friction so as to affect the strength of sediments (Masui et al., 2005; Yang and Zhao, 2014).

In tri-axial compressive tests, due to the existence of the confining pressure, samples of NGH-bearing sediments are under compaction, which can inhibit development of fractures under loading and enhance friction and occlusal force among particles, thereby increasing sample strength (Zhang et al., 2010; Hyodo et al., 2013;Yoneda et al., 2017). With the increase of confining pressure, NGH crystals which can partly play a cementing role are fractured under pressure, which reduces the cementing effect among particles. Accordingly, as the confining pressure increases, NGH-bearing sediment strength increases at a decreasing velocity. Under a great confining pressure, sediment sample strength may drop with the increasing confining pressure (Li et al., 2011).

Temperature also can affect the mechanical properties of NGH-bearing sediments. During mechanical experiments, a lower experimental temperature results in a greater strength of the NGH-bearing sediments. In other words, the strength of NGH-bearing sediments is mainly affected by experimental temperature rather than the temperature corresponding to NGH formation (Hyodo et al., 2007; Jiang and Zhu, 2014). This is mainly due to the fact that the strength of pure NGH increases as the temperature drops (Hyodo et al., 2002).

3.3 The constitutive model of NGH-bearing sediments

During tri-axial compression, NGH crystals may suffer from damages and crushing with the increase of strain (Liu et al., 2016). Because cementing is gradually destroyed under the strain, NGH imposes weakening effect on the mechanical properties of sediments. Therefore, as shown in

Fig. 3, the stress-strain curve of NGH-containing sediments exhibits strong nonlinearity behavior(Yoneda et al., 2015; Li et al., 2016; Yan et al., 2017; Yan and Wei, 2017).

Currently, the constitutive models of NGH-bearing sediments can be roughly classified into two types. Firstly, under elastic-plastic theoretical framework, the mechanical responses of NGH sediments can be reflected by revising the yield function on the basis of traditional geotechnical elastoplastic model such as the Cam-Clay model (Sultan and Garziglia, 2011; Yang and Zhao, 2014)and the Duncan-Chang model (Li, 2013; Miyazaki et al., 2012; Yan et al., 2017) .Due to the limitation of model assumptions, such models can describe the effects of geotechnical elastoplastic deformation of NGH-bearing sediments, reactive hydrate content and occurrence status on mechanical properties of NGH-bearing sediments such as the strength, but different modified models can only consider a single property of NGH-bearing sediments. The complete description on the stress-strain relationship is still inaccurate, and it is difficult to accurately describe the cementation of hydrates between particles. Secondly, by assuming that NGH-containing sediments are elastic materials, constitutive models can be established based on damage theory (Miyazaki et al., 2011; Li et al., 2016; Yan et al., 2018). In the damage model, the stress in the sediment is divided into two parts: soil skeleton stress and hydrate cementation stress. With the increase of sediment strain, the soil particles are relatively displaced or rotated, the hydrate cementation is gradually damaged, and the mechanical influence of cementation is gradually weakened. The damage variable is used to characterize the change of cementation between hydrate and sediment particles during strain development. This type of model is simple in parameter determination and exhibits stronger engineering practicability. At the same time, it can simulate the stress-strain relationship of hydrate sediment samples under triaxial shear conditions, and can reflect the influence of hydrate content and occurrence status on mechanical properties such as stiffness, strength and strain softening of NGH-bearing sediments. However, the constitutive models of NGH sediments based on geometrical damage theory generally assume that the materials after failure lose all bearing capability, which does not conform to actual conditions.

3.4 Numerical simulation on mechanical experiments of NGH-bearing sediments

The mechanical properties of NGH-bearing sediments are closely related to the interaction between hydrates and soil particles. Some scholars have carried out discrete element simulations on the triaxial test of NGH-bearing sediments (Miyazaki et al., 2012; Jiang and Zhu, 2014; Jiang et al., 2018) and examined the microscopic influencing mechanisms of the existence of NGH on the mechanical properties of the sediments. Based on the generalized Hooke's laws, the constitutive model of NGH-bearing sediments under complex stress state were established, including the stress-strain relationship equation, the elastic modulus weakening equation, and the microscopic mechanism for the effect of NGH on mechanical properties of sediments. The results show that the discrete element calculation can characterize the strength and elasticity change of hydrate sediments with the variation of hydrate saturation, and can also explain the intrinsic mechanism of why the mechanical properties of hydrate sediments is complex. The mechanical constitutive model based on discrete element method has few parameters and clear physical meaning.

At present, most of the discrete element simulation are based on the core scale, and there are few studies on the mechanical behavior of large-scale hydrate sediments. Because scholars still have no clear knowledge of NGH-bearing sediment characteristics, selection of reliable simulation parameters still needs to be improved. In addition, it is also reasonable to estimate the mechanical parameters of NGH-bearing sediments based on well logging data (Ning et al., 2013). This is quite mature for conventional gas and oil reservoirs. By contrast, there still exist many complex influencing factors of the mechanical properties of NGH-bearing sediments, but few mechanical experimental data and well logging data are available to date, suggesting that the model still needs more data for accuracy validation.

3.5 Effect of hydrate decomposition on mechanical properties of reservoirs

During NGH exploitation, NGH is gradually decomposed and NGH saturation gradually drops, which can also cause the transformation of microstructures between NGH and sediment particles (for example, the cemented sediments change to pore-filling sediments). Even though NGH is slightly decomposed, stiffness and strength of the reservoirs may also exhibit significant drop (Zhang et al., 2018). According to the research by Priest (Priest et al., 2011), when only 2.9% of the NGH is decomposed, the stiffness of sediments drops by 25%; the decomposition of 15% of the NGH can reduce the stiffness of sediments by 80%. Meanwhile, heat injection can affect the strength of NGH-bearing sediments more significantly than depressurization (Li et al., 2016).

Compared to the conditions where low-permeability formations are difficult to exhaust, the hydrate reservoir can maintain a greater shear strength and shear modulus after decomposition under exhaust conditions. The strength of the CO_2 hydrate sediments is higher than the strength of the methane hydrate sediments while adopting CO_2 replacement method, which provides a certain theoretical guidance for the exploitation of NGH by CO_2 replacement method to maintain formation stability.

The flowing of decomposed gas disturbs the structure of the sand samples, and the strength of the sample after decomposition is therefore less than that of the sample under no NGH formating and decomposing process (Hyodo et al., 2014). If the hydrate is formed in the consolidated and cemented soil skeleton, the hydrate decomposition mainly affects the cohesion, and if it is formed in the non-consolidated soil, the hydrate decomposition mainly affects the internal friction angle(Lu et al., 2018). Additionally, as shown in Fig. 4, the stress condition during the decomposition of NGH-bearing sediment samples and the type of sediments also have a great effect on the strength and deformation characteristics of a sample in decomposition process (Hyodo et al., 2014; Sánchez et al., 2017; Wang et al., 2018). The pressure difference during the decomposition of hydrate can be greater, and the axial strain and volume change can be greater as well. The lower of the confining pressure when the hydrate is decomposed, the more serious damage it will cause. The decomposition rate of hydrate has an effect on the initial deformation, but has little effect on the final deformation.

Scholars now have a preliminary understanding of mechanical properties of NGH-bearing sediments; however, these studies were performed on artificially synthesized sediment samples. According to the mechanical test results of NGH sample from real reservoir from the Nankai Trough of Japan and synthetic NGH-bearing sand samples by Masui et al.(Masui et al., 2007), man-made NGH-bearing samples are different from natural samples in terms of mechanical properties, which can be attributed to different particle size distributions between them. Since few experiments have been performed on natural NGH-bearing samples, more experiments should be performed on natural NGH-bearing samples. How to ensure the similar properties between man-made NGH-bearing samples and natural NGH reservoir is a key issue when use man made NGH-bearing samples for experiments (Gupta et al., 2017). Moreover, NGH saturation of artificially synthesized sediment samples cannot be accurately controlled, which also brings difficulties into relevant studies. Using the synthetic sediment samples, the effects of the micro-distribution pattern of NGH on the mechanical properties of reservoirs are still rarely investigated because the distribution patterns of NGH in sediments also cannot be accurately controlled. Scholars have no thorough understanding of the change in mechanical properties during the NGH decomposition process. There is essentially no research on the mechanical properties of reservoir sediments under crustal stress during the NGH decomposition process. The factors that can affect mechanical properties of reservoirs during NGH decomposition are still unclear. All of these factors significantly affect geomechanical issues of NGH-bearing sediments during the mining process.

4 Borehole instability in NGH-bearing sediments

The study on the mechanical properties of hydrate sediment is to solve the practical engineering problems in the hydrate development process. The first problem encountered in the development is borehole stability during the drilling process. Borehole stability analysis has been widely researched in drilling engineering. Currently, for conventional formations, a set of integrated theoretical systems regarding borehole stability with chemical-mechanical coupling has been established (Chen et al., 2003; Zeynali, 2012; Yan et al., 2017; Chen et al., 2018; Li et al., 2018). Nevertheless, NGH-bearing sediments are still rarely drilled, and the research on borehole stability in NGH-bearing sediments is still in the initial stage. Only a handful of scholars have performed related studies (Birchwood et al., 2005; Ning, 2005; Tan et al., 2005; Freij-Ayoub et al., 2007; Ning et al., 2008; Khurshid et al., 2010; Li et al., 2011; Sun et al., 2018; Zhang et al., 2018).

4.1 The influence factors on borehole stability of NGH-bearing sediments

Because of shallow burial depth and poor formation strength, NGH readily decomposes with disturbances of external environments such as temperature, pressure and salinity changes. Therefore, the response characteristics of reservoirs during drilling of NGH-bearing sediments have aroused great concern (Collett et al., 2010; Birchwood and Noeth, 2012; Li et al., 2018). The friction between the drilling bit and sediments as well as the circulation of drilling fluid may increase the temperature surrounding the boreholes in sediments (Yan et al., 2014), thereby resulting in decomposition of NGH in the formation around the boreholes. Inappropriate selection of a drilling fluid system can further aggravate the decomposition of NGH-bearing sediments, which can lead to decline in NGH-bearing sediment strength and increase of borehole collapse probability (Fig. 5). Because the NGH-bearing sediment skeleton is generally composed of unconsolidated or semi-consolidated sand sediments or argillaceous sandstones, borehole stability becomes particularly important during the drilling of this type of formation. Borehole instability may cause many serious problems such as borehole collapse, jamming of drilling tools, fracture of borehole wall and drilling fluid loss, and even seriously cause scrapping of wells and great loss of manpower and material resources (McConnell et al., 2012;Merey, 2017; Yan et al., 2019).

Under over-balanced drilling or balanced drilling conditions, temperature is the main factor that controls decomposition of NGH in the formation (Zhang et al., 2018). Temperature can also affect the NGH decomposition rate and range. Meanwhile, the seepage of the drilling fluid into the formation and decomposition of NGH results in a change of formation pore pressure, thus affecting NGH decomposition velocity and fluid flow in the pores. Accordingly, the immersion of drilling fluid in the formation actually includes NGH phase decomposition and coupling between the seepage field and temperature field. Fig. 6 displays the coupling relations among various physical fields. Both the seepage field and temperature field affect NGH decomposition, while gas and water produced in NGH decomposition as well as the increasing pores in the formation after decomposition can also affect the seepage field. Concurrently, the heat absorption during NGH decomposition can in turn affect the temperature field. The decomposition of NGH can also bring about change of physical and mechanical properties within the formation, which can simultaneously affect seepage, temperature and deformation fields. Furthermore, the seepage field and deformation field are interactive, and correlated via fluid-solid coupling.

In cases of deepwater oil and gas field development, NGH-bearing regions are generally avoided in the selection of well location so as to avoid accidents during drilling of NGH-bearing sediments and mitigate risks. Deepwater drilling practices may also drill NGH-bearing sediments and experience borehole complexity to varying degrees, which can increase difficulties for drilling operations (Sultan et al., 2004; Nixon, 2005; Eilperin, 2010). By taking the No. 2 production test well in the Nankai Trough of Japan Sea as an example, borehole collapse increased the difficulties during casing installation and well logging; meanwhile, due to borehole enlargement, the usage of cement paste exceeded tank capacity, and an extra 110m^3 cement paste was pumped, eventually leading to poor quality of the well cementing. Borehole stability in the drilling of NGH-bearing sediments is an unavoidable question in the development of NGH resources.

4.2 Numerical Simulation on borehole stability of NGH-bearing sediments

Currently, scholars have mainly investigated borehole stability in NGH-bearing sediments by referring to similar problems in conventional formations. When considering the strong plasticity of NGH-bearing sediments, NGH-bearing sediments are always regarded as elastic-plastic materials when doing borehole stability analysis, and the plastic yield characteristics of the formations around the wells after drilling are typically analyzed based on Mohr-Coulomb yield criterion (Tan et al., 2005; Birchwood et al., 2005; Freij-Ayoub et al., 2007; Sun et al., 2018). The borehole stability analysis in NGH-bearing sediments should comprehensively consider the following phenomenons: fluid flow, heat transfer, mechanical deformation of formation, and weakened formation strength caused by NGH decomposition. They should also analyze the variation of NGH decomposition characteristics and stress around the well, and finally determine the yield rules in the formation around the wells.

Previous studies regarding borehole stability in NGH-bearing sediment simplified the response characteristics of the drilling formation, thereby leading to differences between formation characteristics and practical conditions. For example, Freij-Ayoub et al. did not take heat absorption of NGH decomposition into account and neglected the effect of NGH decomposition on formation temperature field (Freij-Ayoub et al., 2007); Birchwood et al. assumed that the two horizontal principle stresses are identical and used mechanical parameters of tetrahydrofuran hydrate to replace the formation parameters (Birchwood and Noeth, 2012). Assumptions and simplification all resulted in great defects in previous studies. Afterwards, scholars greatly improved and established borehole stability models considering the thermal-hydro-mechanical coupling effect (Cheng et al., 2013;Sun et al., 2018;Zhang et al., 2018); because of the NGH phase change, heat exchange characteristics between drilling fluid and NGH-bearing sediment as well as the effects of NGH decomposition on formation characteristics were considered, the established models are able to determine borehole instability characteristics in NGH-bearing sediments. In addition, several scholars used 3D particle flow model (PFC-3D) for analyzing borehole stability in NGH-bearing sediments, in which sediment skeletons and NGH in the formation were all assumed as particles (Khurshid et al., 2010); nevertheless, NGH decomposition products were not taken into account, therefore the established models can scarcely reflect accurate variation characteristics of formation around the drilling wells.

4.3 The borehole stability controlling of NGH-bearing sediments

According to existing research results, the critical point of borehole stability in NGH-bearing sediment lies in the decomposition of NGH in the formation after the drilling of wells, which can not only reduce the formation strength but also increase water and gas in pores (Sun et al., 2018). The rising temperature can promote NGH decomposition in the formation around the wells. In general, these wells are developed via over-balanced drillings, and the liquid column pressure of the drilling fluid exceeds the pore pressure in the formation. Therefore, unlike conventional drilling of oil-gas wells, the temperature of the drilling fluids rather than density is the most critical factor that affects borehole stability in NGH-bearing sediments. For preventing the decomposition of NGH during the drilling process, America, Canada and China at times employ ground pre-cooling so as to reduce the temperature of drilling fluid and prevent NGH decomposition (Kadaster et al., 2005; Vrielink et al., 2008; Liu et al., 2012).

In addition, chemical agents are generally added to the drilling fluid in the drilling of NGH-bearing sediments for suppressing NGH decomposition in the formation (Merey, 2016). The addition of different inhibitors can impose different effects on NGH phase equilibrium conditions (Zhao et al., 2015). Therefore, NGH is decomposed at different velocities in the formation when different types of drilling fluids are used (Rashid et al., 2014;Zhang et al., 2017; Wang et al., 2017; Zhao et al., 2019), suggesting that borehole stability in NGH-bearing sediments should be evaluated in combination with the drilling fluid performances.

Although scholars have conducted a great deal of research on the effect of NGH decomposition on formation strength, variations of formation strength caused by NGH decomposition under the disturbance of drilling fluid are still scarcely examined. Because NGH decomposition occurs in a limited porous space, the increases of water and gas can increase pore pressure and thus affect the distribution of the stress field in the surrounding sediments of the wells (Ning, 2005; Freij-Ayoub et al., 2007). The increasing amplitude of pore pressure depends on the osmotic coefficient and heating rate of the sedimentary layer. When the formation has poor permeability and NGH can be rapidly heated, gas and water produced during NGH decomposition can flow away in real time, which can lead to a drastic increase of pore pressure (Xu, 2004). Gaining more knowledge of NGH decomposition characteristics and fluid migration in porous sedimentary formations is the key to identifying the effect of NGH decomposition on borehole stability, which requires accurate information of NGH decomposition characteristics and the related effects on formation characteristics under the influence of drilling fluid. However, related studies are far from sufficient. Further, the multi-field coupling theory taking NGH phase change into account during drilling of NGH is also imperfect. All of these factors greatly restrict the accuracy of borehole stability analysis in NGH-bearing sediments.

Conclusively, borehole stability analysis in NGH-bearing sediments is still in qualitative and semi-quantitative stages and requires in-depth investigations of mechanical properties of NGH-bearing sediments and multi-field coupling theory with phase change, so as to provide an accurate prediction of borehole stability changes when specific drilling fluids are used, while also ensuring safe and highly efficient drilling in NGH-bearing sediment.

5 Hydraulic fracturing in NGH reservoirs

While mining after drilling and well completion in sediments, reservoir stimulation is important for enhancing oil and gas production efficiency. Because reservoirs have not been stimulated in previous NGH production tests, NGH productivity in production test wells is overall low, and daily NGH production per well is still too low for commercial exploitation (Liu et al., 2017). It is necessary to propose an effective NGH reservoir stimulation technique (Too et al., 2018).

As a highly mature oil and gas reservoir stimulation technology, hydraulic fracturing now has been widely used in low-permeability oil and gas reservoirs and for the exploitation of gas shale, oil shale and hot dry rocks; it serves as an important method to increase oil and gas well production (Gale et al., 2007; Dahi-Taleghani and Olson, 2011; Heider and Markert, 2017; Gao et al., 2019). Fracturing-induced fractures greatly contribute to promoting productivity of the reservoirs with lower permeability (Zargari and Mohaghegh, 2010). Enhancing reservoir permeability through fracturing plays a critical role in rapidly increasing the shale gas production

(Curtis, 2002; Kim and Moridis, 2015; Guo et al., 2018).

5.1 Experimental study on hydraulic fracturing of NGH-bearing sediments

Currently, scholars mainly follow the same thought of hydraulic fracturing in NGH reservoir stimulation as that in low-permeability plays. Based on geomechanical characteristics, some studies have proposed hydraulic fracturing methods for NGH reservoirs and established related experimental devices; however, these studies have only stayed at the patent level, and there is a lack of actual experiments of hydraulic fracturing in NGH reservoirs (Li et al., 2013; Zhao et al., 2013; An et al., 2018). According to several simulation results, despite loose cementing of the formation, hydraulic fractures can still form in NGH-bearing sediments, as shown in Fig. 7; moreover, tensile fractures are produced in NGH-bearing sediments, which is similar to conventional oil and gas reservoirs in terms of fracture behaviors (Konno et al., 2016; Too et al., 2018a). After fracturing, the permeability of NGH-bearing sediments increases, and productivity can be significantly improved (Too et al., 2018a,b). Because NGH-bearing sediment generally has a lower permeability, far below that of fractures, the permeability of a reservoir with narrowing or reclosed fractures is still far greater than that of the original reservoir (Konno et al., 2016). The above research results demonstrate that hydraulic fracturing is a promising method to increase permeability in low-permeability NGH reservoirs.

5.2 Numerical Simulation on hydraulic fracturing of NGH-bearing sediments

Several scholars have performed numerical simulations on hydraulic fracturing of NGH reservoirs (Chen et al., 2017; Wang et al., 2018), and found that hydraulic fracturing can promote depressurization decomposition of NGH, thereby increasing NGH exploitation efficiency under the sea. Further, fracture length imposes a significant effect while fracture width imposes almost no obvious effect on NGH depressurization exploitation efficiency. The number of fractures also greatly affects NGH exploitation efficiency. With the increase of the number of fractures, NGH depressurization exploitation efficiency can be enhanced and gas-producing rate can also be increased at a decreasing amplitude. Additionally, fracture spacing also significantly affects NGH exploitation efficiency.

The studies regarding hydraulic fracturing on NGH reservoirs have just started. By contrast with conventional oil and gas reservoirs, NGH-bearing sediments have highly complex mechanical properties and more influencing factors in hydraulic fracturing. Questions being proposed and need to be answered include: How can the saturation of NGH and the temperature of fracturing fluid affect hydraulic fracturing performance? How do fractures develop in NGH reservoirs? Both development mechanisms and propagation rules of the fractures in NGH-bearing sediments are so far unclear. Secondly, although existing laboratory tests have confirmed the feasibility of hydraulic fracturing technologies in NGH reservoirs, whether NGH reservoirs can be fractured at all or under which conditions can be fractured still needs validation via field tests because of the strong plasticity behavior of NGH-bearing sediments. Finally, in consideration of low strength and large deformation, traditional fracturing proppants cannot be used in NGH reservoirs. Ensuring the opening of fractures after hydraulic fracturing still remains a challenge for NGH reservoirs.

6 Sand production in NGH reservoirs

6.1 Field tests of sand control in NGH reservoirs

Sand production refers to outward migration of sand particles from reservoirs in the oil and gas exploitation process (Fjar et al., 2008). Sand production is always an important geomechanical problem in oil and gas exploitation from unconsolidated reservoirs (Smith, 1988; Morita et al., 1989; Boutt et al., 2011; Deng et al., 2017). NGH is shallow in burial depth and located in a sedimentary formation consisting of unconsolidated sediments with a high content of fine sands (Zhang et al., 2016); conversely, the pressure difference in depressurization exploitation is always great. Therefore, sand production has become a key problem that restricts safe and high-efficiency NGH exploitation (He et al., 2018). As listed in Table 3, each using different exploitation schemes, different NGH production test projects in different countries including America, Japan, Canada and China all have experienced sand production to varying degrees. The most serious problems have led to some production test projects being terminated in advance because of staggering sand production.

During the exploitation of NGH, a large amount of sand in the produced liquid can cause damage to filtering components in the sand control devices, which then increases sand production and erodes the production pipes (Deng et al., 2017). Even more seriously, sand production may directly or indirectly destroy underwater borehole equipment, gas transmission pipes and other devices, thus triggering disastrous accidents on offshore production platforms and cause great damages to operators and ocean environment (Morita et al., 1989; Deng et al., 2011). Once the sand particles produced from formation deposits in the production pipes (as shown in Fig. 8), both normal operation and production can be affected, and boreholes may even scrape (Deng et al., 2012).

Although some sand control techniques have achieved favorable performances in existing NGH production test projects, NGH reservoirs in different regions exhibit vast differences, especially in terms of reservoir granularity. For example, median grain diameter of the NGH-bearing sediment in South China Sea is below 10μm, which is far smaller than grains in the Nankai Trough of Japan (Fig. 9). Different sand control measures should be adopted in different NGH reservoirs for sand control, i.e., more targeted sand control methods and techniques should be developed in accordance with reservoir characteristics. Therefore, considering the fact that the production time of exiting production tests are generally short and the outputs have not achieved commercial scale, whether the used sand control techniques in production test are applicable to future large-scale commercial exploitation still needs validation.

According to previous hydrate production test and combined with NGH reservoir characteristics, the sand production problem may be unavoidable in the process of hydrate production, so it is necessary to prevent sand production. The key to sand production is sand control, which allows some small sand particles to enter the wellbore, blocking most of the sand outside the wellbore, and minimizing the impact of sand-control measures on production capacity while ensuring the safety of the wellbore. The maximum amount of sand allowed in the production process should be studied in the next step. From the production testing case, the formation deficit caused by early sand production in the reservoir can result in structural instability of the reservoir and then cause damage of the sand-control tool and gravel layer and lead to the large-scale sand production, which may be the main reason for the failure of sand control in the pilot production. In the following research, establishing an early warning mechanism for large-scale sand production (structural instability of the reservoir) of the NGH reservoirs can help to make preparation for the sand discharge treatment and production system adjustment in time to reduce the impact of sand production, which is useful to stable mining of reservoirs. At the same time, when doing research about the special equipment for hydrate exploration, the sand treatment capacity of the mining platform should be enhanced to cope with possible problems of sand production, and the impact of sand production on hydrate mining should be minimized.

6.2 Laboratory tests on sand control of NGH-bearing sediments

Because of high cost and long periods of field sand control tests, the simulation of sand production process in NGH reservoirs in the laboratory is an important means of acquiring NGH sand production data and investigating NGH sand control technologies. Scholars have mainly focused on the analysis of sand production and sand-prevention schemes in previous sand production and sand-control simulations on NGH reservoirs.

With the use of a core displacement sand production device, Oyama et al. (2010)conducted sand production experiments during the NGH depressurization process and found that sand particles were mainly produced in the unstable NGH depressurization process. Moreover, water flowing through pores rather than NGH-decomposed airflow served as the driving force of sand production, and water flow velocity was the main factor that affected the degree of sand production.

Suzuki and Kuwano (2016) performed one-dimensional cylinder water permeability tests on the produced sand particles from Japan’s first NGH production test in 2013. By selecting the backfilling gravels with a diameter of 450 μm as the sand control media, actual reservoirs were simulated using the mean particles sizes from the production test. Based on the simulated migration behaviors of the fine particle components, no large-scale sand production was observed; however, as the flow increased, the extrusion of fine sand particles was observed, which does not conform to significant sand production in actual production test.

Based on Japan’s first NGH production test data, Murphy et al. (2017)investigated sand production behaviors under two critical conditions-loose and compacted sand particles. They concluded that the sand production mechanism is correlated with sediment porosity and confining pressure. Under uniform flow, loose sand particles moved overall but the sand structure remained stable; by contrast, local sand production appeared in compacted sand, thereby resulting in the formation of large holes. It can thus be speculated that Japan’s NGH production test in 2013 was performed on loose-sand reservoirs, during which overall sand production rather than local sand production with stable sand structures was observed.

Jung et al. (2011) did a research emphasis on the effect of fine particles on NGH development; based on experimental results on submarine simulation devices, the relative geometric size between fine silt particles and throat restricted the migration of fine silt particles, blocking the pores. They also concluded that even a very low content of fine silt particles can affect NGH exploitation.

Based on depressurizing NGH marine production data and reservoir characteristics in Japan, Lee et al. (2013) and Qiu et al. (2015) performed evaluation experiments of sand-control techniques and determined that conventional commercial sand-control methods were effective. By combining prevention methods for coarse particles and dredging of fine particles in the design of their control techniques, Li et al. (2017) proposed the design of a gravel sand-control backfilling layer for argillaceous silty NGH reservoirs in the Shenhu area of South China Sea.

The sand control experiments of NGH in laboratory is an important measure to explore the sand-control method of NGH reservoirs, but the existing simulation experiments for sand control in hydrate reservoir in laboratory are still rare, and most of them are aimed at the research on decompressing production process under a special condition (mainly the pilot production of hydrate from Japan in 2013). It lacks systematically sand-control experimental analysis and has no regular understanding of the matching relationship between sand-control method and reservoir characteristics, and there is no simulation experiment of sand production under other production methods. Moreover, these laboratory experiments are all about what methods should be used for sand control in research, and there is no in-deep research on why the sand-control method adopted in the existing pilot production is failed. This research may play a guiding role for the subsequently design of sand-control schemes. The existing sand-control experiments of hydrate mainly focus on the migration of sand particles in the formation and the blocking effect of sand-control media on sand particles, but lacks the study of sand particles on blocking rules of sand-control mechanism.

Laboratory tests of sand control in NGH exploitation are important means of exploring sand-control methods in NGH reservoirs; however, because NGH is non-uniformly distributed in the artificially-prepared samples, test devices cannot truly simulate some environmental factors such as crustal stress in the subsurface, thereby leading to deviations between the test results and field production test results. Exploring new experimental methods and devices is still necessary so as to better simulate the production in NGH reservoirs. Meanwhile, the actual experimental process is restricted because artificial preparation of NGH-bearing sediments is quite time-consuming. Finally, the limited amount of experiments are still unable to establish a relationship between sand-control media and particle size grading in NGH reservoirs. In the next step of the research, it is very important to establish a comprehensive influence of sand-control medium, particle size, production parameters, reservoir strength and other factors on sand-control and production performance through a large amount of laboratory experiments, which can provide references for the selection of appropriate sand-control measures in the next pilot production and commercialization.

6.3 Numerical simulations on sand production from NGH reservoirs

NGH sand production experiments also exhibit many disadvantages including poor uniformity of artificially-synthesized NGH-bearing sediments, uncontrollable NGH saturation, difficulties in observing sand production process and temporal/spatial evolutionary process of reservoir characteristics. By contrast, fluid-solid-thermal-chemical coupling numerical simulations can simulate detailed sand production process in NGH reservoirs and analyze the overall sand production mechanisms through the coupling of temperature field, seepage field, stress field and NGH phase change in the reservoirs; meanwhile, the extension of sand-control experiments on laboratory spatial/temporal scale to field spatial/temporal scale can provide guidance for field exploitation. Several scholars have performed some numerical simulations on sand production in NGH reservoirs.

Currently, numerical simulations on sand production in NGH reservoirs are mainly focus on the analysis of sand production mechanisms. There exists two root causes that account for sand production in the exploitation of hydrate reservoirs—concentration of stress in near-well area after drilling and reduction of reservoir strength induced by NGH decomposition (Cheng et al., 2010;Yan et al., 2018). These related factors can both affect sand production in NGH reservoirs.

Because serious sand production problems appeared in Japan’s marine NGH production test in 2013, Uchida et al. established a theoretical model of thermal-hydraulic-mechanical sand production for analyzing the migration process of sand particles in the production test and the occurrence position of sand production(Klar et al., 2013; Xu et al., 2014; Zhou et al., 2014; Uchida et al., 2016); they concluded that the combined action between the non-uniform distribution of stress in the reservoir caused by the non-uniform distribution of NGH saturation and pressure difference during production triggered shear failure in the reservoir. This therefore cause sand particles to be transported into the well via the fluid flow.

Traditionally, NGH numerical simulation software (TOUGH_HYDRATE) has been the primary software used to analyze NGH productivity during the exploitation process (Li et al., 2012; Moridis et al., 2007) but it fails to simulate the stress state in the production. Several scholars combined TOUGH_HYDRATE and FLAC3D or ABAQUS (commonly-used in rock mechanics) to explore sand production mechanisms in the development of NGH reservoirs (Rutqvist and Moridis, 2007; Moridis et al., 2010; Sun et al., 2017; Yan et al., 2018). According to their results, shear failure is also the core factor that accounts for sand production in the reservoir.

During the production of NGH, as the production pressure difference increases, the decomposition range of hydrate increases within the same time frame, which also results in the decline in the strength of hydrate reservoir. Meanwhile, the increase of production pressure difference can also reduce the support the fluid provides on the borehole wall and increase the concentration of stress in the near-well area. Therefore, a larger production pressure difference causes a more serious sand production problem in a hydrate reservoir (Lu et al., 2017). During the production of hydrate, a higher well temperature is more favorable for the decomposition of hydrate, and accordingly, sand production is more serious in the NGH reservoir (Shen et al., 2012). Borehole temperature imposes less of an effect on sand production in the reservoir than pressure difference during the production (Yan et al., 2018).

Reservoir characteristics also greatly affect sand production in the NGH reservoir (Yan et al., 2018). If the horizontal crustal stress is more non-uniformly distributed in the NGH reservoir, the concentration of stress around the borehole is more severe, and sand production is more serious in the reservoir. The reservoir permeability can affect the propagation velocity of pore pressure. In a reservoir with larger permeability, the pore pressure in the formation around the well more rapidly drops, and the hydrate is more rapidly decomposed and sand production is more serious in these reservoirs. The decomposition of the hydrate with larger saturation imposes more intensive disturbance on the reservoir strength, thereby inducing more serious sand production.

Meanwhile, sand particles in loose sediments produced after the failure of formation do not necessarily flow into the well with the fluid. In fact, there exists a critical flow velocity that these loose sand particles can only start to move when the seepage velocity of the fluid in the reservoir exceeds this value (Liu et al., 2017). Therefore, water production during the development of hydrate can also significantly affect sand production.

Currently, scholars have conducted numerical simulations on sand production process in NGH reservoir for analyzing sand production mechanisms in open-hole completion, while the effect of sand-control completion mode on sand production has not been taken into account. The completion method in NGH well changes the boundary conditions in multi-field coupling model calculations and the distribution of seepage-stress-strain in the near-well formation, thereby affecting sand production in the reservoir. The adoption of sand-control measures can prevent sand particles carried by the fluid from flowing into the well. The flowing sand can also cause certain blockage to the sand-control medium, which reduces the permeability of the sand-control layer and the capacity from the perspective of long-term production. The evaluation of the performance of sand-control measures in the life cycle of hydrate wells and its impact on production should also be a focus of the next numerical simulation research.

According to the development history of pilot hydrate mining test, the prediction of sand production and the development of sand-control design technology under different mining modes is lagging behind the trial mining project itself. At present, no sand-control method of NGH exploitation can be considered as promotional. Therefore, theoretical research in this area must be strengthened. Due to the huge cost of the hydrate mining test, the number of hydrate mining test is very limited, and it is impossible to verify the effects of different completion methods on site. Therefore, it is necessary to further the research in laboratory experiments and numerical simulation to promote the development of sand prediction and sand-control technology, and combine the laboratory experimental simulation and numerical simulation with the real field test to realize the mutual integration between the laboratory simulation results and in-situ practice. In this way, it can provide guidance for the completion method in the pilot mining and commercial development process.

7 Geological disasters caused by NGH decomposition

Seabed NGH-bearing sediments have a shallow depth and low strength, most of which exhibit no complete trap structures and dense cap sediments. Therefore, large-scale NGH development can easily trigger a series of geological disasters such as settlement and landslide on the seafloor (Zhu et al., 2015), which can endanger the marine environment and human's ecological environment. The occurrence of these geological disasters should be avoided (Birchwood et al., 2005; Rutqvist and Moridis, 2008; Fereidounpour and Vatani, 2014)

7.1 Reservoir settlement induced by NGH decomposition

Scholars have conducted a great deal of research on the settlement of reservoirs during conventional oil and gas exploitation (Gutierrez, 1994; Zaman et al., 1995; Yin et al., 2015; Jongerius, 2016; Thienen-Visser and Fokker, 2017). However, the established models and the related research methods on seabed and ground sediments in traditional oil and gas reservoir development cannot be directly applied to the development of NGH reservoirs because of their unique properties. Scholars have just begun to investigate the compaction of NGH-bearing sediment and the effects on drilling operations.

The decomposition of NGH can significantly reduce reservoir strength (Zhang et al., 2018). As the exploitation continues, NGH is gradually decomposed and the region of NGH-bearing sediment where the strength drops starts to expand (Gong et al., 2015; Yan et al., 2018). Gas produced by NGH decomposition is transported to the sea surface via a recovery device and stored. Because gas and water are constantly pumped from the reservoir, the effective stress in the reservoir increases, which can cause compaction within the sedimentary formation after NGH decomposition and trigger seabed settlement.

Because of a lack of large-scale commercial NGH exploitation activities to date, the effects of long-term commercial exploitation on seabed settlement have not been experimentally investigated. Currently, scholars have mainly conducted numerical simulations or laboratory tests on the effect in the development process, and found that NGH development can cause large-area seabed settlement. Furthermore, the settlement amount mainly depends on the production method, pressure drop amplitude, reservoir characteristics and mining time. In particular, the mining time imposes significant effects on seabed settlement. With the increase of production time, the settlement range and amount undergo a significant increase (Gong et al., 2015). Long-term exploitation can cause seabed subsidence with a depth of up to several meters (Fang, 2010; Kim et al., 2012). Seabed subsidence amount under long-term NGH exploitation in horizontal wells far exceeds that in vertical wells (Moridis et al., 2010; Kim et al., 2012; Qiu et al., 2015). Existing NGH production tests were performed in vertical wells. No report of significant seabed settlement during the production test in vertical wells does not mean that no settlement in horizontal wells will occur. Serious seabed settlement may threaten the stability of drilling equipment on the sea floor and pose incredible threats to operation safety of other subsea facilities such as seabed cables and pipes (Borowski and Paul, 1997; Sahling et al., 1999; Hovland and Gudmestad, 2001; Li et al., 2018).

From the perspective of NGH-bearing sediment characteristics, seabed settlement in NGH exploitation process is unavoidable. In the next step of research, scholars should think deeply on what can be done to alleviate seabed subsidence and the effects of seabed subsidence on environmental and engineering issues.

7.2 Seabed landslide and environmental problems caused by NGH decomposition

When the NGH exploitation zone is located below the seabed slope, the decomposition of NGH can remarkably reduce the stability of the seabed slope and may trigger large-scale seabed landslides (Sultan et al., 2004; Pedley et al., 2010; Micallef et al., 2012; Mountjoy and Micallef, 2012; Song et al., 2019). And many natural geohazards of seabed landslide were caused by NGH decomposition. For example, the Storegga Landslide, the largest-scale seabed slide to date, occurred mainly because of NGH decomposition (Sultan et al., 2004); large-scale landslides on continental slopes near the Gisborne coast, Agadir Basin Landslide, Amazon Landslide and Cape Landslide are all connected with NGH decomposition to varying degrees (Maslin et al., 2005; Wien et al., 2007; Mountjoy et al., 2009; Hunt, 2012)

Serious seabed landslides can trigger the occurrence of many other natural disasters, such as seaquakes and tsunamis (Hornbach et al., 2007; Grozic, 2010), which can further cause NGH decomposition and an enormous release of methane. Methane is a greenhouse gas with 21 times more potent than carbon dioxide according to the assigned global warming potential over 100 years (Change, 2007) . Because of the large amount of methane found as methane hydrates in nature, a “clathrate gun” hypothesis has been suggested (Kvenvolden, 1993,1999; Dickens et al., 1995; Archer, 2007; Maslin et al., 2010). It is postulated that ocean warming could cause natural widespread dissociation of methane hydrate and lead to the release of methane into the atmosphere, which will further increase the amount of greenhouse gases in the atmosphere. While this issue in itself is very important, it should be highlighted that methane hydrates in nature, according to their in-situ conditions, are easy to destabilization (Boswell and Collett, 2011). Therefore, the prevention of geological disasters and greenhouse gas leakage induced by NGH exploitation is a precondition of NGH development.

NGH-bearing sediments as well as the overlying and underlying strata are poor in permeability. With regard to seabed landslides induced by NGH exploitation, large-scale NGH decomposition can greatly reduce reservoir strength; meanwhile, gas and water produced during NGH decomposition cannot overflow from the reservoir in time, and pore pressure in the reservoir rapidly increases, thereby leading to a gradual decrease of effective stress in the reservoir and the liquidation of the reservoir in serious cases. When NGH-bearing sediment is located in an inclined formation, the reservoir can evolve into a sliding surface, and the upper formation slides downhill along the produced horizon after NGH decomposition (Fig. 10) (Sultan et al., 2003; Wan et al., 2016). Meanwhile, the decomposition of NGH also causes a decline in the solid volume and strength of the reservoir and upward movement of the underlying strata, which may further accelerate damages on the side slopes related to NGH decomposition (Kvenvolden, 1994;Kvenvolden, 1998).

In general, seabed landslides induced by NGH decomposition can occur when the following conditions are satisfied (Dillon et al., 1998). Firstly, NGH is widely distributed. Secondly, an instable region on the side slope is located in a NGH stable region so that it can be further affected by NGH decomposition. Finally, the bottom of NGH-bearing sediments includes low-permeability or no-permeability regions, which are favorable for the formation of high pore pressure.

The stability of NGH-bearing seabed slide slope is controlled by various factors, including the depth of overlying sea water, burial depth, thickness and saturation of NGH-bearing sediment, the angle of side slope and NGH decomposition degree (Sultan et al., 2004; Xu and Germanovich, 2006; Sultan, 2007). It is now well-accepted that NGH decomposition can lead to decline in the stability of the seabed slope or even trigger seabed landslides; however, existing studies are limited to only seabed landslides caused by the decomposition of marine NGH under natural conditions (Sultan et al., 2003;Wan et al., 2016). The effects of long-term, large-scale NGH exploitation on seabed stability and especially the occurrence of seabed landslides, and the relevant measures for preventing the occurrence of large-scale seabed landslide are still rarely investigated. Seabed landslides induced by NGH decomposition may still occur on the side slope at a gradient below 5° (Leynaud et al., 2004; Liu et al., 2010). Therefore, the rick of potential landslide caused by the decomposition of NGH should be fully evaluated before the exploitation of NGH-bearing sediments on a side slope.

8 Conclusions and prospect

Commercial exploitation of NGH is a systematic project. Inappropriate exploitation and construction modes may trigger a series of environmental and safety problems. Therefore, we should be cautious for large-scale commercial development of NGH, and fully evaluate the effect of NGH exploitation on the environment.

At present, production tests of NGH are conducted in vertical wells. According to existing the drilling results, as long as reasonable drilling measures were adopted, maintaining borehole stability and ensuring successful drilling and subsequent well-completion practices was not a large issue. However, because vertical wells always have low productivity in NGH compared to their horizontal counterparts, it is necessary to exploit NGH using horizontal wells from the perspective of increased productivity. The existing borehole stability analyses were all performed on vertical NGH wells. Whether previous research results are applicable to the development of NGH in horizontal wells still needs further validation. In particular, when performing some operations such as sand control after well drilling, maintaining long-term borehole stability in long horizontal wells so as to prevent borehole collapse, and incapability of placement of sand control tools should be a research emphasis. Based on the existing research, there are two possible methods to maintain the long-term borehole stability of the NGH-bearing sediments. One is to prevent the decomposition of hydrates during drilling, which can be solved from its temperature and pressure conditions to reduce the decomposition of hydrates by reducing the temperature of the drilling fluid, adding decomposition inhibitors to the drilling fluid, or using chemical stabilizer to form a specific reinforcement membrane on the borehole for reducing mass and heat transfer between the sediments and the borehole. Another method is using casing drilling and doing real-time sealing for well drilling, eliminating the impact of borehole collapse on subsequent operations.

Sand production is an unavoidable problem in the NGH exploitation process. Currently, scholars have mainly adopted traditional oil-gas sand control measures in NGH-bearing sediments; however, traditional oil-gas sand control measures mainly aim to prevent the production of coarse-particle sand and fail to prevent argillaceous fine silt with fine particles. Many NGH-bearing sediments have small sedimentary particles (for example, median particle diameter in the South China Sea is <10μm). The key to sand control in NGH-bearing sediments lies in the control of sand particles, i.e., small sand particles entering into the borehole while large sand particles blocked by sand control media. Determining the maximum ratio of sand content in the produced liquid in the well during the exploitation of NGH is crucial for safe and high-efficiency NGH exploitation. Sand content in exploration can not only ensure safe production but also avoid the decline in productivity caused by sand control media. This research should be combined with specialized equipment for hydrate exploration. Since the traditional deep water oil and gas exploration equipment is expensive, and the operation depth of hydrate exploration is less than that of deep water oil and gas, it is necessary to construct special equipment for hydrate exploration to reduce the cost, and the sediment concentration of the produced liquid in hydrate mining should match with the operational capabilities of these specialized equipment. The next step about research on sand control of hydrate sediments should focus on the gradation relationship between the pore size of the sand control medium and the particle size of the sediments, and determining the sand control design criteria for the hydrate sediments. The gradation relationship determines the clogging law of the sediment particles against the sand control medium and the degree of the sand shield blocked by the sand control medium, which is the basis for the future design of the hydrate sand control tool. Although the adopted sand control measures have achieved favorable results in some NGH production tests, whether these methods are applicable to commercial exploitation still needs further investigation.

Reservoir stimulation is an important measure for raising NGH production, which mainly focuses on hydraulic fracturing. Traditional hydraulic fracturing is mainly applied to brittle stratum, but hydrate sediments belong to strongly plastic stratum, which are generally difficult for fracture initiation and propagation. Although laboratory experiments have demonstrated the feasibility of hydraulic fracturing in hydrate sediments, there is still a lack of validation of fracture initiation and propagation in the actual hydrate reservoirs of the seabed. If fractures cannot be created in the field actual sediments, we can take measures to enhance the fracture ability of the hydrate sediments (e g, injecting liquid nitrogen into the sediments to enhance the brittleness). Because NGH-bearing sediments are generally shallow in burial depth and possess no fully-developed overlying or enclosed strata, the fractures induced by hydraulic fracturing can easily penetrate into the overlying strata, leading to the leakage of methane and occurrence of environmental disasters. Therefore, the application of hydraulic fracturing in NGH-bearing sediment stimulation should be cautious and the possible consequences should be fully evaluated before the application. NGH differs greatly from traditional oil and gas resources in occurrence mode, and traditional hydraulic fracturing is not necessarily applicable to the stimulation of NGH-bearing sediments. Several other novel reservoir stimulation methods may be more applicable to NGH-bearing sediments and should be explored for increasing NGH productivity.

NGH exploitation may also trigger geological disasters such as seabed landslides. However, this issue is still poorly investigated. The development of NGH resources should take both economy and possible environmental effects into overall consideration. NGH development and the caused stratum depletion have the potential to induce seabed landslides. Hydraulic fracturing can damage the structure of reservoirs and increase the risk of seabed landslides. In order to reduce the risk of geological disasters caused by hydrate development, we should evaluate the risk of disaster occurrence fully before starting development, and do real-time monitoring of the response of soil during the development process. With regards to possible geological disasters, occurrence mechanisms should be fully analyzed, and the most important aspect to investigate is how to reduce the occurrence of risks. For example, the use of some measures should be adopted in production or reservoir stimulation so as to overall strengthen the reservoir. In addition, for the complex conditions of deep-sea environment, the most currently disaster research caused by hydrate decomposition is carried out for a single factor such as decomposition. It also requires in-depth research on conditions, scale, and possible disaster chain and prevention of disasters with the development of combined actions between hydrate decomposition and external environmental loads such as earthquakes, typhoons and internal waves.

As stated above, NGH reservoirs differ greatly from traditional oil and gas reservoirs in occurrence characteristics, and traditional oil and gas exploitation methods are not necessarily appropriate. Exploring new production methods other than traditional oil and gas exploitation may be another way of achieving commercial development of NGH resources. To achieve this, the development of NGH resources should not only be an extension of the traditional oil and gas industry, but also need to encourage workers to actively participate the related industries in society, thus breaking the thought of traditional oil and gas exploration. It is more conducive to form the special mining methods for developing NGH.

It is undisputed that NGH is one of the largest sources of hydrocarbon on earth and also a potential source of clean hydrocarbon-based energy for humanity in the near future. Given the unique geographical distribution and vast resource quantity of NGH, the production of natural gas from NGH is expected to have far-reaching impacts on global economy than the production of shale gas. In spite of certain achievements, there is still a long way to go before the commercial development of NGH resources. Researchers should overcome difficulties and make persistent efforts, with the aim of fulfilling economic, safe and green NGH exploitation as soon as possible.

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Fig. 1. Distribution diagram of proven NGH reservoirs all over the world (Grace et al., 2008; Krey et al., 2009; Kvenvolden and Rogers, 2005).

Fig. 2. Variation diagram of micro-distribution during the formation of synthetic CH_4 hydrates in the sediments(Gao-Wei et al., 2014), in which CH_4 hydrates, NaCl solution, quartz sand and CH_4 gas are marked in yellow, grey, light grey and black, respectively. (saturation of hydrate: a，3.9%；b，24.6%；c，35.0%；d，51.4；e，97.0%).

Fig. 3. Stress-strain curve of NGH-bearing sediments (Yoneda et al., 2015).

Fig. 4. Damage to NGH-bearing sediments induced by NGH decomposition and stress condition (Sánchez et al., 2017).

Fig. 5. Illustration of borehole instability in NGH-bearing sediments.

Fig. 6. Coupling relations among various physical fields in NGH-bearing sediment borehole stability analysis.

Fig.7. Some visual fractures observed during hydraulic fracturing of synthetic methane hydrate-bearing sand specimens using red-dye water (Too et al., 2018a;b;c)

(a) Crack-line fractures captured in the specimens used in the hydraulic fracturing tests. The crack-line is marked by arrows while puncture the hole with a dashed box. The crack plane is oriented horizontally.

(b) Vertical fractures along the injection pipe axis observed in the specimens.

Fig. 8. Illustration of sand production from NGH-bearing sediments.

Fig. 9. Particle size distributions in NGH-bearing sediments (Luo et al., 2016;Hyodo et al., 2014).

Kaolin clay: Median Diameter 5.455μm Specific gravity 2.60g/cm^3

Marine sediment: Median Diameter 7.189μm Specific gravity 2.70g/ cm^3

Toyoura sand: Gs=2.635 g/ cm^3 e_{max}=0.973 e_{min}=0.613

Fig. 10. Illustration of seabed landslide induced by NGH decomposition.

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Table 1 Statistics of NGH production methods used in the production tests (Grace et al., 2008; Kurihara et al., 2010; Fujii et al., 2013; Zhang et al., 2013; Saeki, 2014; Abendroth et al., 2014; Kvamme, 2015; Konno et al., 2015; China Geological Survey Bureau, 2017; Zhou et al., 2017; Oyama and Masutani, 2017; JOGMEC, 2017; Su et al., 2018; Wu and Wang, 2018; Zhou et al., 2018; Chen et al., 2018)

Production test region	Reservoir characteristics	Reservoir type	Production test time	Production method	Period and effect
Messoyakha Field, Russia	Burial depth: 700-800m Thickness: 84 m Porosity:16-38% NGH saturation: 40%	Tundra NGH	1969-1989	Depressurization and injection of chemical agent	Intermittent production for 17 years, in which 36% production was from NGH decomposition
Mackenzie Delta, Canada	Burial depth: 800-1100 m Thickness: 110 m Porosity: 29.3% NGH saturation: 47%	Tundra NGH	2002	Injection of hot saline water and depressurization	470m^{3}gas was produced in five days
			2007	Depressurization and heat injection	830 m^3 gas was produced in 12.5 hours
			2008	Depressurization	13000m^{3}gas was produced in six days
Alaska, America	Burial depth: 650-900m Thickness: 40-130m Porosity: 40% NGH saturation: 60-75%	Tundra NGH	2012	CO_2 replacement and depressurization	5946 m^3 gas was injected after the injection for 13 days 28316 m^3 gas was produced in 30 days
Nankai Trough, Japan	Water depth: 1000 m Burial depth: 1270-1330 m Thickness: 50-84 m Porosity: 45% NGH saturation: 60%	Coarse sand reservoir in the sea	2013	Depressurization	120000m^3 gas was produced in 6 days
			2017	Depressurization	35000m^3 gas was produced in 12 days
			2017	Depressurization	2200000m^3 gas was produced in 24 days
Shenhu Area, South China Sea	Water depth: 1266 m Burial depth: 203-277 m Thickness:30-60m Porosity: 38-45 NGH saturation: 31-34%	Clay-silt reservoir in the sea	2017	Depressurization	309000m^3 gas was produced over 60 days
Liwan District, South China Sea	Water depth: 1310 m Burial depth: 117 -196 m Thickness: 60 m Porosity: 43% NGH saturation 40%	Clay-silt reservoir in the sea	2017	Solid fluidization method	81m^3 gas was produced

Table 2 Comparison of properties between ice and NGH (Waite et al., 2000)

Property	Ice	Hydrate
Vp/Vs	1.98±0.02	1.93±0.01

Poisson's ratio	0.33±0.01	0.317±0.006
Shear modulus（Gpa）	3.6±0.1	3.2±0.1
Adiabatic bulk modulus（Gpa）	9.2±0.2	7.7±0.2
Isothermal bulk modulus（Gpa）	9.0±0.3	7.1±0.3
Adiabatic Young's modulus（Gpa）	9.5±0.2	8.5±0.2
Isothermal Young's modulus（Gpa）	9.1±0.3	7.8±0.3

Table 3 Statistics of sand-prevention techniques in NGH production test (Grace et al., 2006; Zhang et al., 2007; Yamamoto and Dallimore, 2008; Zhang, 2013; Terao et al., 2014; Chee et al., 2014; Collett et al., 2014; Saeki, 2014; Yamamoto et al., 2014; Hauge et al., 2014; Matsuzawa et al., 2014; Sun and Zhang, 2015; Qiao et al., 2015; Qiu et al., 2015; Zhang et al., 2016; Li et al., 2016; Liu et al., 2017; Oyama and Masutani, 2017; Lu et al., 2017; Zhou et al., 2018)

Production test region	Production method	Production test time	Sand-control technique	Sand-control performance
Messoyakha Field, Russia	Depressurization and injection of chemical agent	1969-	Perforation completion	Sand production in weakly commented NGH reservoirs
Mackenzie Delta, Canada	Injection of hot saline water and depressurization	2002	Mechanical sand control	Sand production
	Depressurization and heat injection	2007	Perforation completion without sand control	Serious sand production causing damages to ESP
	Depressurization	2008	Mechanical sand control and arrangement of sand-prevention nets at the pump inlet	Sand production
Alaska, America	CO_2 replacement and depressurization	2012	Perforation sieves for sand control	Sand production
Nankai Trough, Japan	Depressurization	2013	Combination of open-hole gravel packing and sand-control sieve tubes	Serious sand production that caused the failure of ESP and the termination of production test in advance
	Depressurization	2017	Pre-expansion Geoform sand-control system	Failure in sand control and burial of borehole with sand particles
	Depressurization	2017	Downhole expansion Geoform sand control system	Favorable
Shenhu Area, South China Sea	Depressurization	2017	Sand control in non-diagenetic ultra-fine reservoirs	Effective sand control
Liwan District, South China Sea	Solid fluidization method	2017	Without sand-control measures	Separation of sand, gas, water and NGH in the lifting pipes

Declaration of Interest Statement

We would like to submit the enclosed manuscript entitled "Geomechanical issues in the exploitation of natural gas hydrate", which we wish to be considered for publication in "GONDWANA RESEARCH". No conflict of interest exits in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Graphical abstract
Geomechanical issues induced by NGH decomposition

Highlights

1. Decomposition of NGH causes a significant decrease in reservoir strength.
2. NGH production may cause borehole instability, sand production, seabed landslide.
3. New reservoir stimulation methods should be explored to enhance NGH productivity.

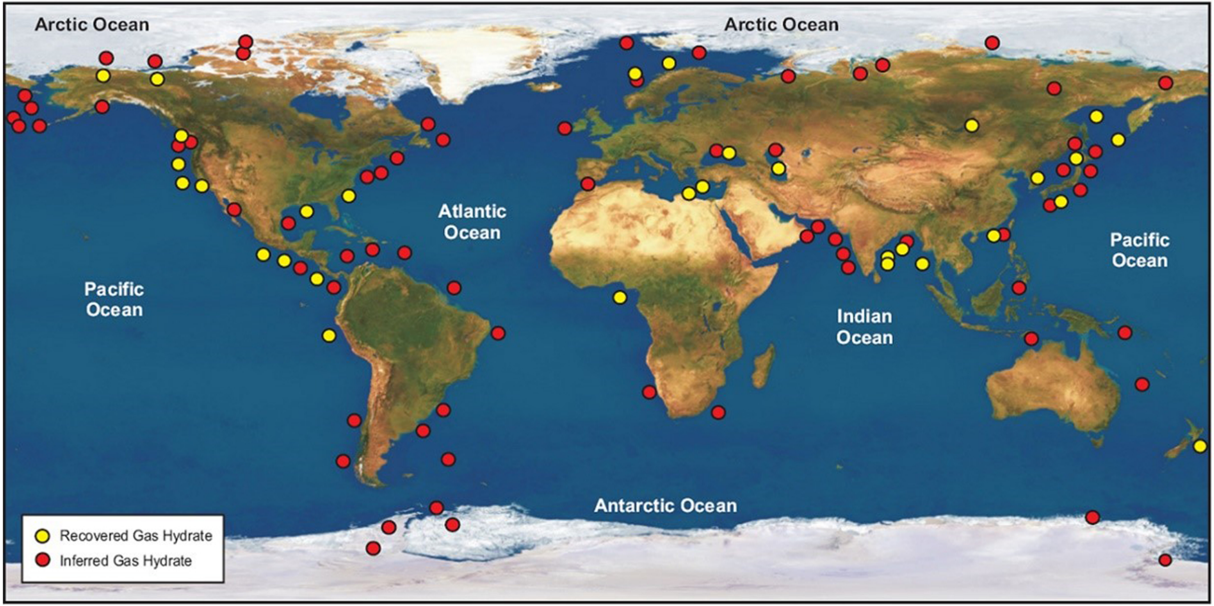

Arctic Ocean
Arctic Ocean
Atlantic Ocean
Pacific Ocean
Pacific Ocean
Indian Ocean
Antarctic Ocean
Recovered Gas Hydrate
Inferred Gas Hydrate

Figure 1

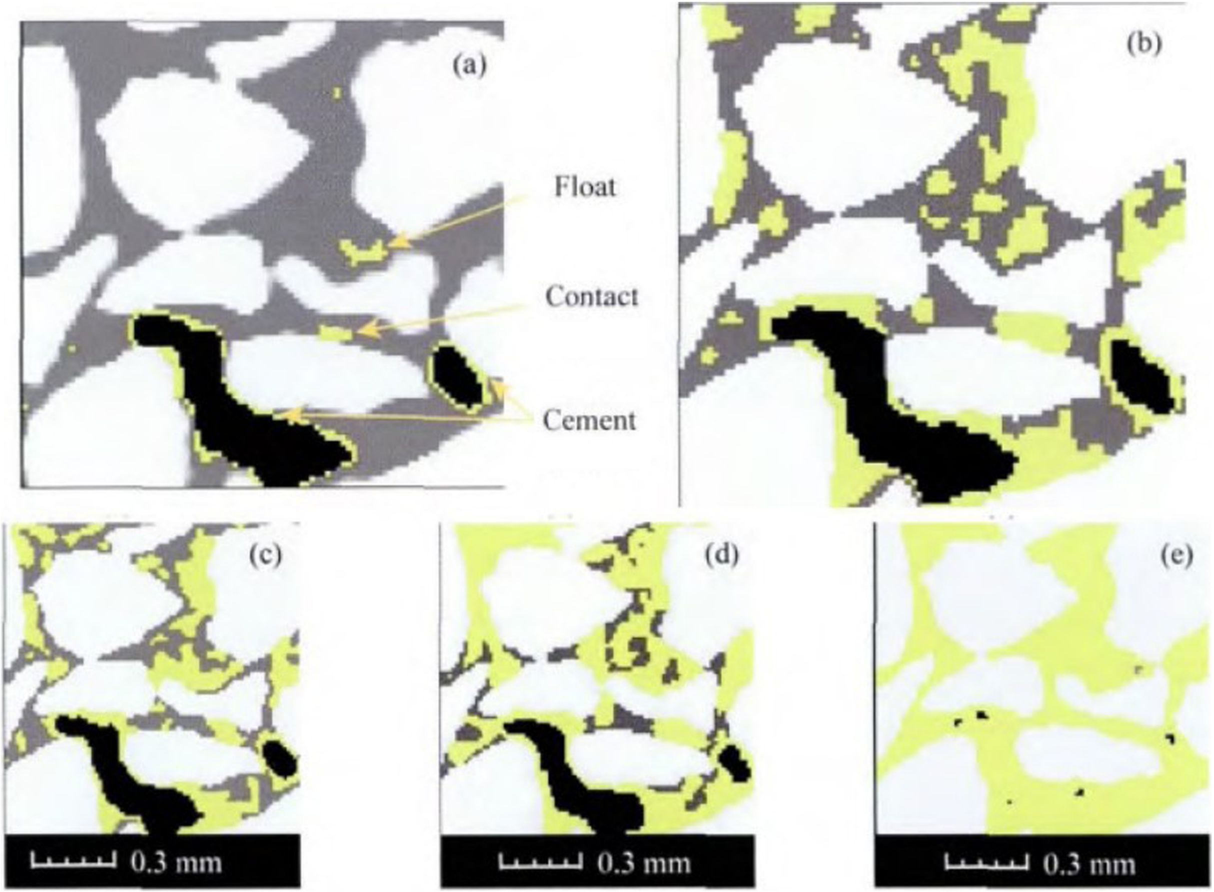
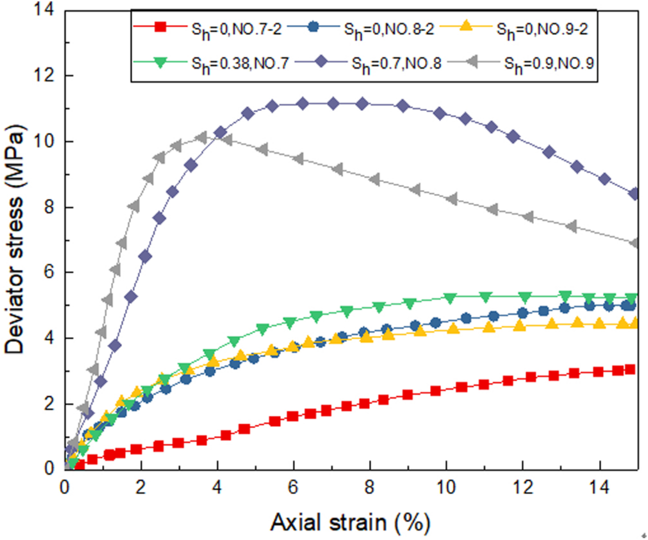


Figure 2



S_h=0,NO.7-2
S_h=0,NO.8-2
S_h=0,NO.9-2
S_h=0.38,NO.7
S_h=0.7,NO.8
S_h=0.9,NO.9
Deviator stress (MPa)
Axial strain (%)
0
2
4
6
8
10
12
14

Figure 3

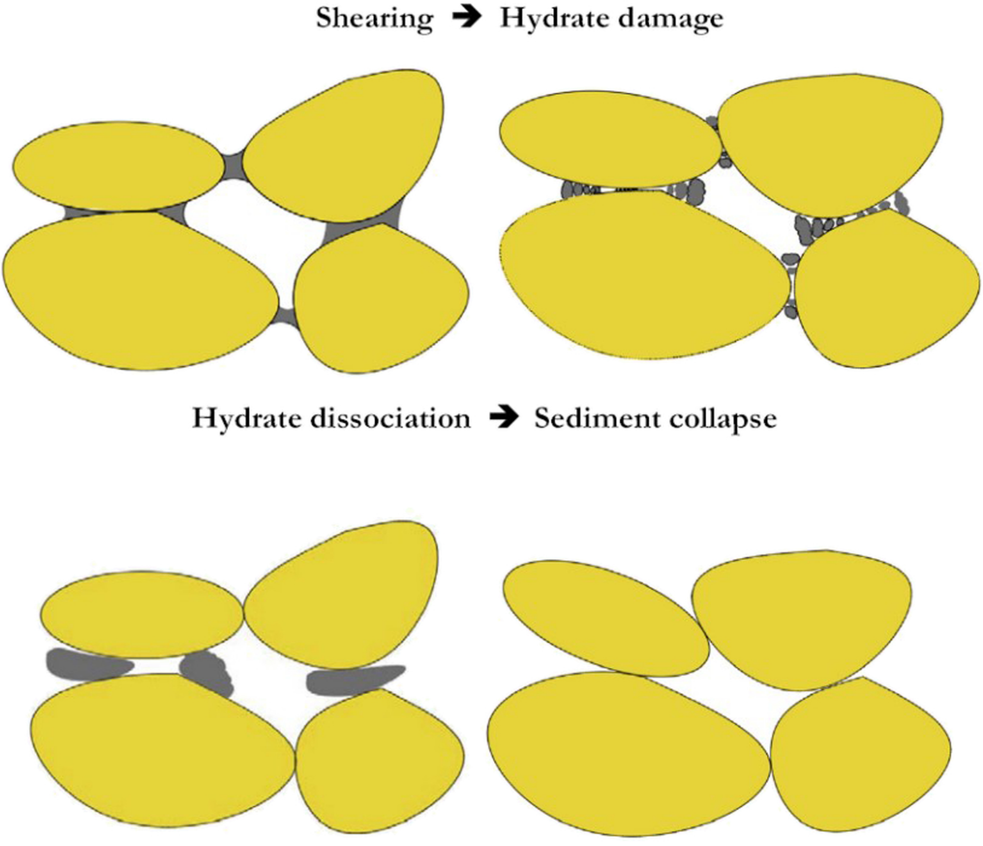

Shearing ➔ Hydrate damage
Hydrate dissociation ➔ Sediment collapse

Figure 4

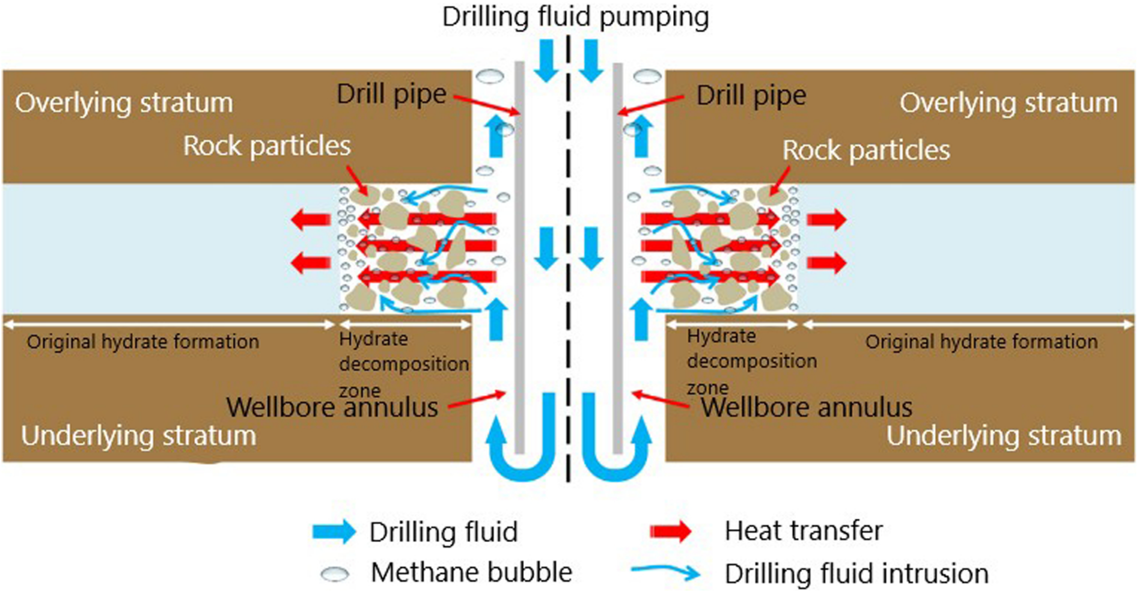

Drilling fluid pumping
Overlying stratum
Drill pipe
Rock particles
Drill pipe
Overlying stratum
Rock particles
Original hydrate formation
Hydrate decomposition zone
Hydrate decomposition zone
Original hydrate formation
Wellbore annulus
Underlying stratum
Wellbore annulus
Underlying stratum
Drilling fluid
Heat transfer
Methane bubble
Drilling fluid intrusion

Figure 5

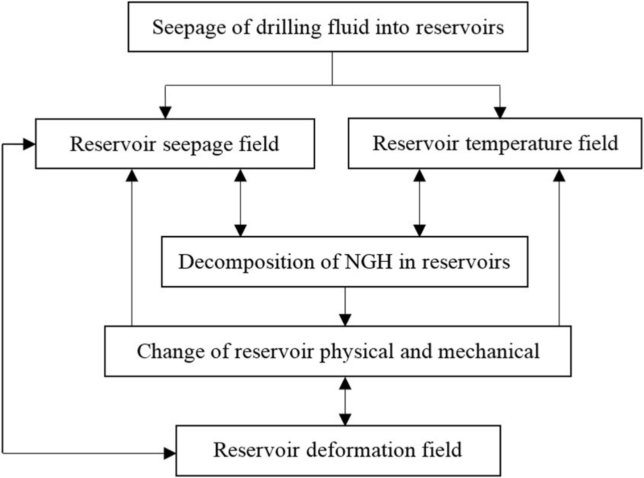

Seepage of drilling fluid into reservoirs
Reservoir seepage field
Reservoir temperature field
Decomposition of NGH in reservoirs
Change of reservoir physical and mechanical
Reservoir deformation field

Figure 6

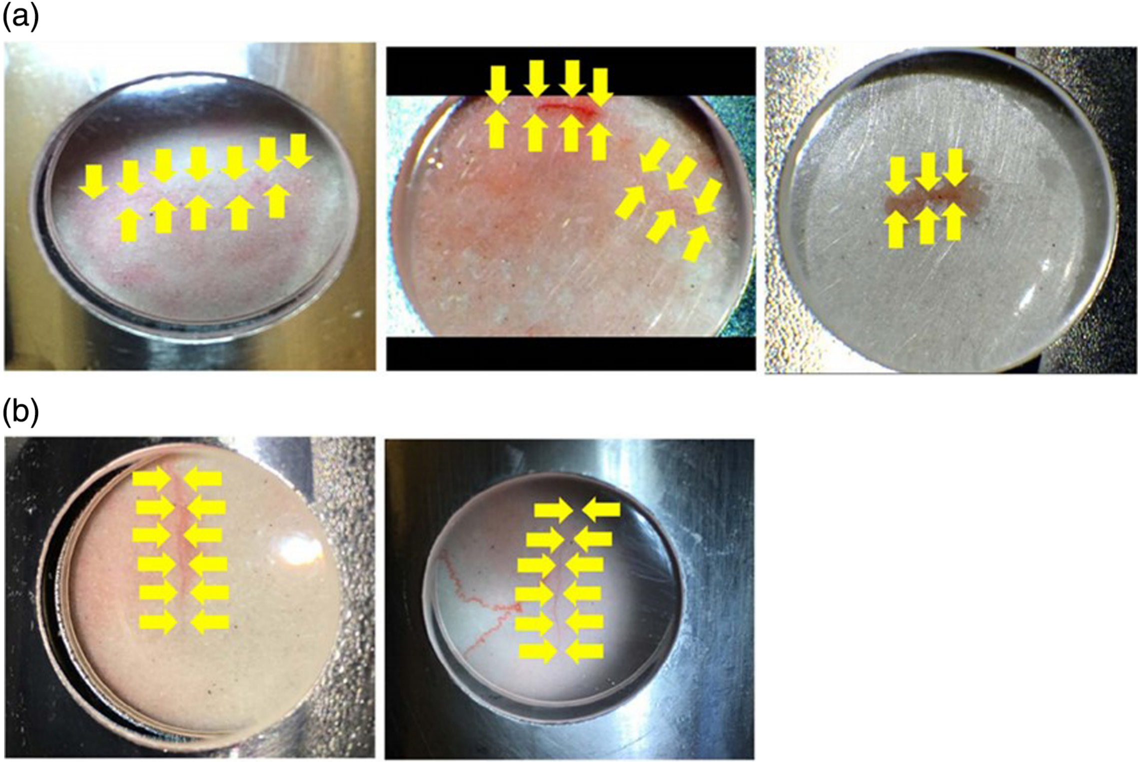


Figure 7

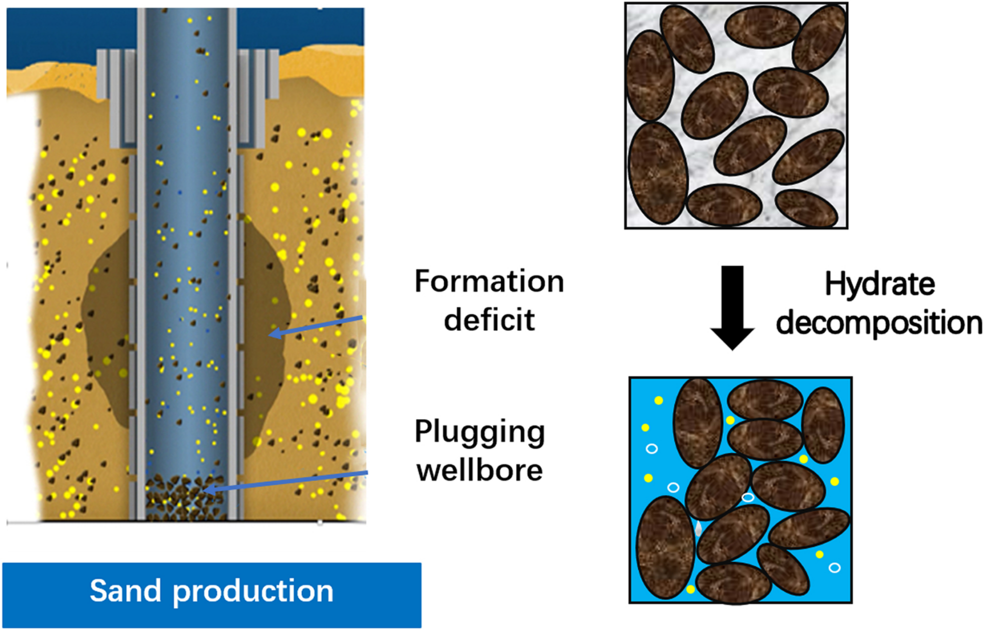

Formation deficit
Plugging wellbore
Hydrate decomposition
Sand production

Figure 8

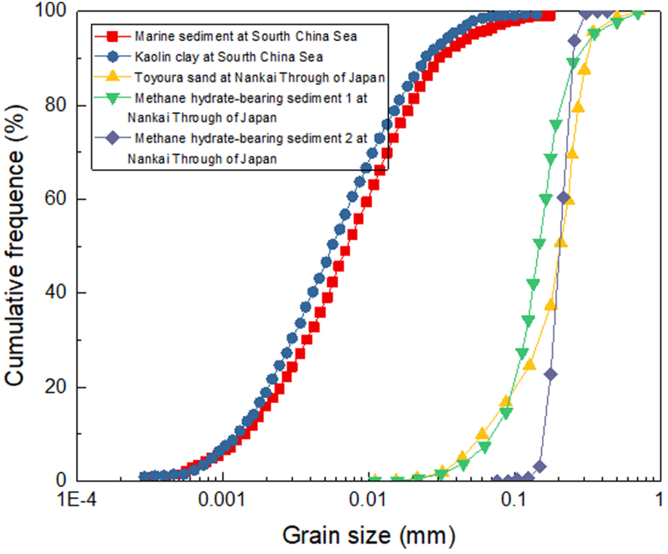

Marine sediment at Sourth China Sea
Kaolin clay at Sourth China Sea
Toyoura sand at Nankai Through of Japan
Methane hydrate-bearing sediment 1 at Nankai Through of Japan
Methane hydrate-bearing sediment 2 at Nankai Through of Japan
Cumulative frequence (%)
0
20
40
60
80
100
1E-4
0.001
0.01
0.1
1
Grain size (mm)

Figure 9

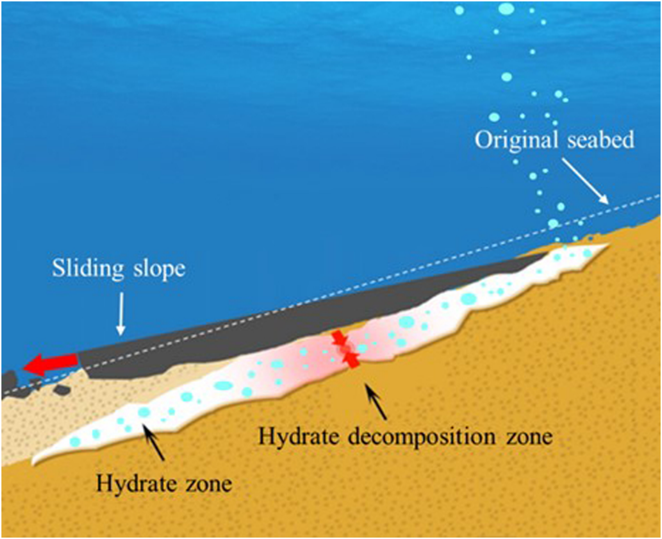

Original seabed
Sliding slope
Hydrate decomposition zone
Hydrate zone

Figure 10