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Stability analysis of a wellbore in hydrate bearing sediments using PFC3D

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ABSTRACT

Drilling in hydrate bearing sediments (HBS) has many uncertainties and challenges, because the most of the HBS distribute in a deep-see floor where hydrate dissociation can affect the stability of a wellbore. Understanding of the mechanical behavior of the HBS is a very important issue in HBS drilling. In this study, the stability of the wellbore drilled in the HBS was analyzed by using PFC3D, a DEM commercial code. The micro-parameters were determined through the triaxial tests in order to obtain the macro properties of the model. The triaxial tests were numerically simulated until the model showed the friction angle and the cohesion obtained from the laboratory experiments on the specimens from site (UBGH 2-2-2, UBGH 2-6 and UBGH 2-10).

The stability of a wellbore in the HBS was analyzed using the geometry based on the site investigations. The effects of the drilling rate and the range of dissociation were examined. The average displacement of the surface and the number of cracks significantly increased as the zone of dissociation expanded, while they were not affected by the drilling rate. The increase in hydrate saturation degree caused the instability of the hydrate formation regardless of the material properties.

1. INTRODUCTION

Gas hydrates are created by gas molecules under low temperature and high pressure conditions, similarly to ice. Gas hydrates are distributed at relatively shallow depths below the seafloor. Gas hydrates have the merit of emitting less carbon dioxide than other fossil energy sources because they are mainly composed of methane (Sloan, 1998). The worldwide amount of gas hydrates is conservatively estimated to total 25 times what has been proven, approximately ten trillion tones in the world. It corresponds to twice the amount of all known fossil fuels on earth. The deposit in East Sea of Korea is estimated at 600 million tons that can meet Korea's natural gas needs for about 30 years. For the commercial production of gas hydrates in the HBS, the stability of the drilled wellbore must be guaranteed. The hydrate dissociation caused by

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change in temperature and pressure can lead to the subsidence of ocean floor and the reduction in cohesive strength, which consequently affects the stability of the facilities and equipments for drilling and production (Park, 2008). Therefore, the mechanical behavior and stability should be examined thoroughly prior to the drilling in HBS.

Recently, attempts have been made to develop the theoretical model of the wellbore stability. Birchwood et al. (2005) presented a wellbore stability model based on the mechanical properties of THF (TetraHydroFuran) gas hydrates. They developed the model to describe the dilation, stress and strain according to friction angle and temperature distribution according to drilling rate. Freij-Ayoub et al. (2007) explained the mudcake played a considerable part in increasing the bonding strength between the particles these studies however have focused on the effects of individual parameters on wellbore stability based on two dimensional analyses. In this study, the stability of the wellbore drilled in the HBS was analyzed by three-dimensional particle flow code, PFC3D. The wellbore stability was quantified based on the simulation results including an average displacement and the number of cracks. In this study, the stabilities of the wellbores at the target sites (UBGH 2-2-2, 2-6, 2-10) in East Sea of Korea were numerically analyzed.

2. Numerical model

2.1 Determination of micro-parameters in PFC3D

In this study the three dimensional particle flow code, PFC3D, were employed to simulate the wellbore in the HBS and the dynamic behavior of assemblies of arbitrarily sized spherical particles. The PFC3D represents a material as an assembly of rigid spherical particles that move independently of one another and interact only at the contact points. These unknown properties at contact and particle levels require tedious calibration process of micro-parameters until the macro-scale response of a model agrees with the results of laboratory tests. In order to determine micro-parameters, the triaxial test model was simulated and repeated until the friction angel and cohesive strength of the model agrees with the results of laboratory tests on the target sites. In Table 1, the laboratory test results of the specimens obtained in the UBGH second drilling expedition are provided.

Table 1. Formation properties of UBGH in East Sea of Korea

Site	Grain density (kg/m^3)	Cohesive strength (MPa)	Friction angle (°)
UBGH 2-2-2	2,650	2.5	29.2
UBGH 2-6	2,650	2.5	26.5
UBGH 2-10	2,600	2.5	26.0

Three different confining pressures were applied to the numerical simulation on each model: 5, 10 and 15 MPa. Table 2 and Table 3 show the conditions of the triaxial compressive tests on the numerical models and the finally determined micro-parameters, respectively. Generally, triaxial test is not appropriate to determine the micro-parameters because PFC3D model cannot reproduce the material with high friction angle. However, gas hydrate formation has relatively the low friction angle compared to other solid materials, e. g. rock mass.

Table 2. Test conditions and result of PFC3D triaxial test

Site	Test condition				Numerical test result	
UBGH 2-2-2	Confining Pressure (MPa)	5.0	10.0	15.0	Cohesive(MPa)	2.5
	Max. Strength (MPa)	23.0	37.0	49.8	Friction angle(°)	29.0
UBGH 2-6	Confining Pressure (MPa)	5.0	10.0	15.0	Cohesive(MPa)	2.5
	Max. Strength (MPa)	23.0	37.0	49.8	Friction angle(°)	26.5
UBGH 2-10	Confining Pressure (MPa)	5.0	10.0	15.0	Cohesive(MPa)	2.5
	Max. Strength (MPa)	23.0	37.0	49.8	Friction angle(°)	25.8

Table 3. Micro-parameters for PFC3D models

Site	Grain density (kg/m^3)	Normal contact bond (Pa)	Shear contact bond (Pa)	Stiffness ratio	Friction coefficient
UBGH 2-2-2	2,650	12e6	12e6	1.0	0.5
UBGH 2-6	2,650	10e6	10e6	1.0	0.45
UBGH 2-10	2,600	9.2e6	9.2e6	1.0	0.56

2.2 Simulation of wellbore stability

The stability of a wellbore in the HBS was analyzed using the geometry of the HBS model was based on the UBGH second drilling expedition and micro-parameters determined by the procedure described in the section 2.1. Dynamic behavior of the model was simulated, and the induced micro-cracks and displacements of the particles around the surface were monitored in the simulation. The micro-crack indicates the bond breakage at the contact between particles, and the particle displacement means total displacement of each particle that was generated during the dynamic simulation. The dissociation of solid gas hydrates was simulated by reducing the particle size and being null. It was assumed that only temperature change influenced on the dissociation and the reverse reaction did not occurred. The rate of dissociation was set to be constant because the kinetic reaction and the increase in pressure due to dissociation were not considered in this simulation. The temperature distribution of HBS can be calculated using the condition of drill fluid and temperature of layer observed in the site investigation and Fourier's heat conduction law. The maximum distance influenced by the heat conduction was 0.3 m from the wellbore center (Tan et al., 2005).

Based on the site investigation, the thickness of the deposit in East Sea is less than 1.5 m. Therefore, the model was made width(1.2m) x height(1.8) m. The initial model is generated using the micro-parameter in table 3. Gas hydrate is randomly distributed in the sample. The number of formation grains are 7,328 and the number of hydrate particles are 4,213. The average particle radius is 2.8×10^{-2} m. Figure 1 shows the initial formation model and figure 2 shows the numerical test result by using PFC3D.

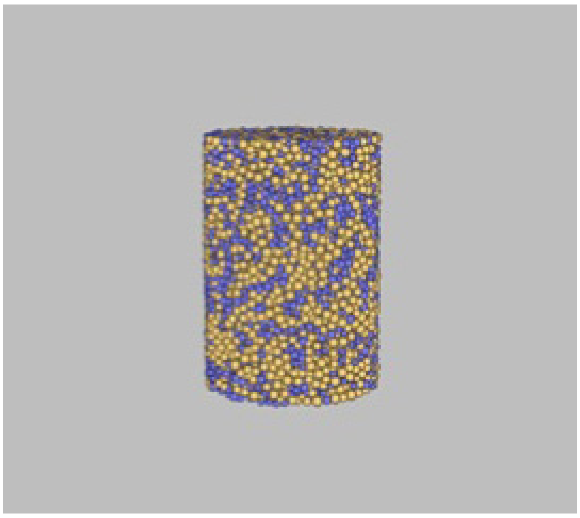
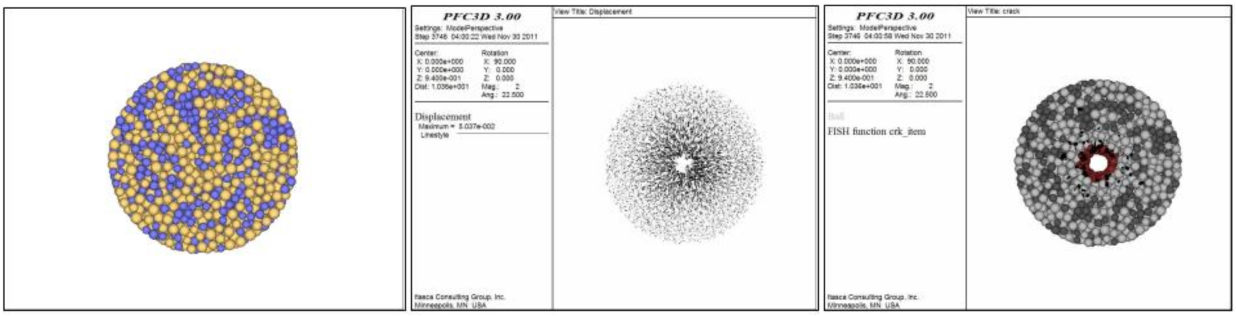


Fig. 1 Initial Model



(a) Sample **(b) Displacement** **(c) Crack**

Fig. 2 Numerical simulation result

3. Results and Discussions

The dissociation of gas hydrate bearing formation caused the particle displacement and crack while drilling in PFC3D. Numerical simulations were carried out according to the dissociation range, gas hydrate saturation and drilling rate at each target site(UBGH 2-2-2, 2-6, 2-10) and evaluated the average displacement, crack numbers and wellbore failure. Table 4 shows the results of simulation.

The average displacement and the number of cracks increased as the gas hydrate saturation increased. With the hydrate saturation of higher than 60%, wellbore failure was occurred in the conservative drilling condition. With the hydrate saturation of 70%, displacement took place higher than 5% of sample size. This means that we need to pay attention to deep formation drilling because target sites are of higher than 50% of porosity and high gas hydrate saturation.

The wellbore stability analysis were carried out to evaluate the influence of dissociation range by changing the dissociation range from 0.13m to 0.26m and estimate the average particle displacement and the crack amount. The average displacement and the number of cracks increased as the dissociation range increased and in case of the two times dissociation range, the average displacement and the number of cracks increased about 1.5 times.

When hydrate formation has high gas hydrate saturation, as the dissociation range increased, the particle displacement and the number of crack rapidly increased. The wellbore stability analysis was carried out to evaluate the influence of drilling rate by changing the drilling rate from 36 m/hr to 72 m/hr. The average displacement and the number of cracks slightly increased as the drilling rate increased while wellbore stability is not affected. In PFC3D, rock crushing according to the increase of the drilling rate was not simulated because the particles were assumed to be rigid body..

Table 4. Simulation results

(a) UBGH 2-2-2

Depth (mbsf)	GH saturation (% of pore vol.)	Dissociation range (m)	Drilling rate (m/hr)	Average displacement (cm)	Crack num.	Failure
100	29	0.13	36	1.98	720	No
		0.26	36	3.09	880	No
		0.13	54	2.10	720	No
		0.13	72	2.15	780	No
120	40	0.13	36	2.66	820	No
		0.26	36	3.59	1120	No
		0.13	54	3.1	940	No
		0.13	72	3.15	960	No
145	67	0.13	36	3.61	1,220	No
		0.26	36	9.93	5,760	Yes
		0.13	54	8.22	3,920	Yes
		0.13	72	8.55	4,320	Yes

(b) UBGH 2-6

Depth (mbsf)	GH saturation (% of pore vol.)	Dissociation range (m)	Drilling rate (m/hr)	Average displacement (cm)	Crack num.	Failure
115	45	0.13	36	2.66	900	No
		0.26	36	3.65	1140	No
		0.13	54	3.14	920	No
		0.13	72	3.18	980	No

130	53	0.13	36	3.85	900	No
		0.26	36	8.26	1920	Yes
		0.13	54	4.05	1060	No
		0.13	72	4.16	1220	No
145	70	0.13	36	8.98	4600	Yes
		0.26	36	11.09	8,640	Yes
		0.13	54	9.05	5,080	Yes
		0.13	72	9.93	5,560	Yes

(b) UBGH 2-10

Depth (mbsf)	GH saturation (% of pore vol.)	Dissociation range (m)	Drilling rate (m/hr)	Average displacement (cm)	Crack num.	Failure
100	20	0.13	36	1.98	720	No
		0.26	36	3.05	900	No
		0.13	54	2.21	800	No
		0.13	72	2.22	820	No
150	40	0.13	36	2.73	960	No
		0.26	36	4.44	1360	No
		0.13	54	3.44	1100	No
		0.13	72	3.47	1160	No
170	60	0.13	36	3.95	1280	No
		0.26	36	8.59	4,680	Yes
		0.13	54	4.42	1,360	No
		0.13	72	4.56	1,420	No

4. Conclusion

The stability of the wellbores at the target sites (UBGH 2-2-2, 2-6, 2-10) in East Sea of Korea is numerically analyzed by using PFC3D. In the simulations, the effects of the dissociation range and the drilling rate were examined.

In PFC3D, determination of the micro-parameters is one of the most important procedure. We calibrated the micro-parameters by simulated triaxial tests repeatedly. Until the model showed the friction angle and the cohesion obtained from the laboratory experiments on the specimens obtained in the sites.

Based on the parametric study, the range of dissociation and the degree of saturation turned out to be important factors to affecting the wellbore stability. With fixed the dissociation range, the average particle displacement and the number of cracks significantly increased as the gas hydrate saturation increased. Wellbore wall failed when the degree of saturation exceeded 60 %.

Although the drilling rate did not show any significant effect on the wellbore stability in all the simulations in this study, the displacement and the number of micro-cracks increased as the drilling rate increased at high degree of gas hydrate saturation. In consideration of the high porosity and higher than 50 % of gas hydrate saturation degree in the target sites, the drilling procedure should be carefully planned based on the analysis of the temperature as drilling fluid and the formation.

Acknowledgments

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