



Numerical Prediction of Seabed Subsidence with Gas Production from Offshore Methane Hydrates by Hot-Water Injection Method

Hiroki Matsuda¹, Takafumi Yamakawa¹, Yuichi Sugai², Kyuro Sasaki²

¹Graduate School of Engineering, Kyushu University, Fukuoka 819-0395, Japan

²Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan

***Corresponding Author:** Kyuro Sasaki, Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan

Abstract: Seabed subsidence is studied by comparing experimental data with the results of a numerical model for gas production from an offshore methane hydrate (MH) reservoir using the hot-water injection method. To predict seafloor displacement, geo-mechanical reservoir models, such as the consolidation–permeability compound model, are required to simulate MH dissociation and consolidation by depressurization in the MH reservoir. In this study, we constructed a field-scale model of gas production from a MH reservoir induced by hot-water injection using dual horizontal wells. Compared with the depressurization method, this method required less depressurization to produce the same amount of gas with pressure drawdown up to 10MPa. This causes less seabed subsidence; therefore, the hot-water injection method is a more environmentally friendly gas-production method for offshore MH reservoirs.

Keywords: Methane Hydrate, Offshore Gas Production, Consolidation, Subsidence, Hot-Water Injection

1. INTRODUCTION

Methane hydrates (MHs) are seen as the next-generation natural gas resources. Most MHs are preserved in marine sediments or permafrost. The MH potential in the offshore 900-km² area in the Eastern Nankai Trough off the Pacific coast of Honshu, Japan, was estimated to be roughly equal to the Japanese domestic gas consumption over a 10-year period (Fujii et al., 2008)^[1]. Furthermore, recently a promising MH layer was found based on strong bottom simulating reflector (BSR) observed along seismic line transect across site NGHP-01-05 in India (Shankar, 2016)^[2].

To produce gas from MH reservoirs, methods such as depressurization, thermal stimulation, inhibitor injection, and injection of N₂, CO₂, or a mix of the two gases have been proposed and studied to enhance in-situ MH dissociation while considering the MH equilibrium condition (Pooladi-Darvish, 2004)^[3]. If conventional offshore drilling and gas production methods are applied, the depressurization method has been evaluated as an economical method for extracting gas from MH reservoirs (Masuda et al., 2002)^[4]; (Kurihara et al., 2009)^[5]; (Matsuda et al., 2016)^[6]. Therefore, in March 2013, the first offshore MH production test was carried out by applying the depressurization method at the Eastern Nankai Trough, and approximately 120,000 m³ of natural gas were produced in 6 days. Morid et al. (2010)^[7] presented excellent reviews on the commercial gas production from MH reservoirs. Silpngarm et al. (2012)^[8] developed the compositional simulator for methane-hydrate system, and they carried simulations applied by a constant bottom hole pressure implemented as a production scheme.

In the depressurization method, the bottom-hole pressure (BHP) at the producer is reduced by lowering the hydraulic head by pumping up water into the producer, and the MH dissociation process in the reservoir begins after the lower pressure propagates from the producer. The depressurization must continue to maintain the gas production rate or the MH dissociation rate. The MH dissociation rate is proportional to the rate of heat transfer to the MH from the surrounding sand and water with the available sensible heat. Sensible heat depends on the difference between the initial temperature and MH equilibrium temperature corresponding to the MH pressure after depressurization.

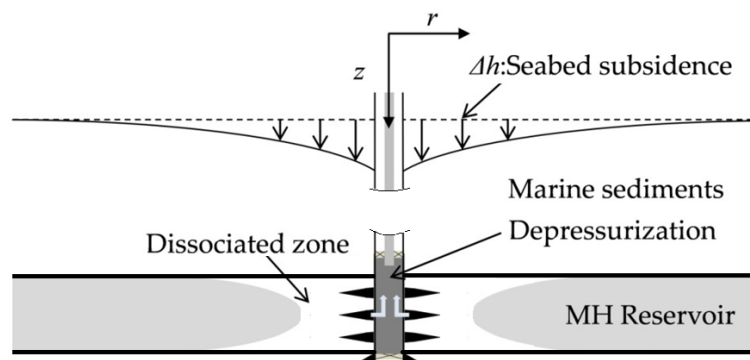
However, depressurization and the decrease of solid saturation resulting from MH dissociation induce

consolidation of the MH reservoir and nearby sediments, leading to subsidence of the seafloor environment. This subsidence is the combined deformation of the three-dimensional consolidation in the sediment layers below the seabed. The depressurization causes an increase in the effective stress and reduces the fluid permeability; this lowers the pressure propagation speed and the gas mobility in the MH reservoir. As a result, MH dissociation and gas production are suppressed by these interdependent processes.

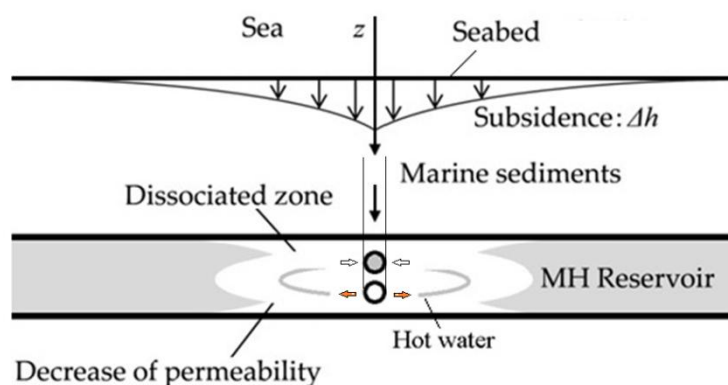
Reservoir consolidation and seabed subsidence are important issues that need to be addressed when discussing the seafloor environment and its mechanical stability. Therefore, our research group proposed a method that uses hot-water injection using horizontal wells at lower depressurization of MH reservoirs to provide a thermally efficient method that has less environmental impact on the seabed floor (Sasaki et al., 2010, 2014)^{[9],[10]}. However, the group did not investigate the relation between seabed subsidence and gas production from MH reservoirs and whether hot-water injection has an advantage to reduce the subsidence.

In this study, a numerical model combining models of MH dissociation and consolidation has been presented to simulate seabed subsidence with gas production from a MH reservoir by hot water injection with a pair of horizontal wells using the thermal simulator CMG STARSTM (2015version). The consolidation model was constructed by history matching with laboratory experimental results carried out by Sakamoto et al.(2009, 2010)^{[11],[12]}. The model includes the reservoir rock mechanical stiffness function of MH saturation and consolidation. Numerical simulations for typical MH reservoirs on a field-scale were carried out to predict the gas production and consolidation behavior. From the point of view of seabed subsidence and heat supply, the method using hot-water injection with relatively low depressurization was studied by comparing the gas production and seabed subsidence characteristics with those of the depressurization method with high depressurization.

2. NUMERICAL MODELS



(a) Depressurizing method using a single vertical well



(b) Hot water injection method using a pair of horizontal wells

Fig1. Schematic showing gas production from methane-hydrates reservoir and consolidation by depressurizing and hot-water injection using a pair of horizontal wells

2.1. General Concept of The Model

Once the depressurization method is applied to a reservoir, the pore pressure decreases, and the effective stress (= confining stress – pore pressure) increases. Furthermore, MHs include favorable conditions for consolidation as the effective stress increases, because the MH reservoir consists unconsolidated turbidite sedimentary-structure at the Eastern Nankai Trough, Fig. 1 shows the coordinate system of the numerical model of MH reservoir consolidation and seabed subsidence where $z(m)$ is depth from seabed and $r(m)$ shows radial distance from the single well.

2.2. Numerical Modeling of MH Dissociation

The reservoir simulator STARS was used for numerical simulation of the gas production and consolidation based on MH dissociation and the elasticity function of MH saturation. In the simulations, MH was defined as a solid phase; a power function describes the reduction in absolute permeability caused by saturation of the MH reservoir porosity (Masuda et al., 2002)^[4]. According to Singh et al.(2008)^[13], the MH dissociation rate can be calculated by the MH formation-decomposition equilibrium curve and the Arrhenius equation for phase transition from solid to fluid phase. Other thermal quantities and the MH decomposition heat were given based on the compositions (solid, gas, and water) in the MH reservoir blocks. The numerical model was constructed as a multi-phase fluid flow and temperature distribution.

2.3. Models of Porosity, Permeability, and Consolidation

The increasing of MH saturation (solid phase) induces a sharp decrease in the relative permeability due to the decrease of apparent porosity in the MH reservoir. Conversely, the apparent porosity and permeability increase rapidly because of MH dissociation. In addition, the porosity that depends on the congenital compressibility of the MH reservoir is reduced because of the increase in effective stress with depressurization. In this numerical simulation, the effective porosity, which depends on MH saturation, compressibility, and depressurization are defined by Equations (1) to (3), respectively.

$$\phi_v = \phi_i \cdot \exp[\kappa(p - p_i)], \quad (1)$$

$$\kappa = 3(1 - 2\nu)/E, \quad (2)$$

$$\phi_e = \phi_v(1 - S_{MH}), \quad (3)$$

where

ϕ_v : Porosity [-]

ϕ_i : Initial porosity [-]

κ : Compressibility [1/Pa]

ν : Poisson's ratio [-]

E : Elastic modulus of reservoir [Pa]

p : Reservoir pressure [Pa]

p_i : Initial reservoir pressure [Pa]

ϕ_e : Effective porosity [-]

S_{MH} : MH saturation [-].

The initial permeability of the MH reservoir is remarkably low at the initial condition of high MH saturation (>0.5); however, the apparent permeability of the MH reservoir improves rapidly with MH dissociation (Masuda et al., 2002)^[4]. However, the porosity of the MH reservoir decreases because of consolidation resulting from depressurization. Therefore, the absolute permeability of the MH reservoir decreases. To represent the permeability–porosity relationship, we use Eq. (4) based on the Kozeny–Carman equation (Nimblett and Ruppel, 2003)^[14].

$$k = k_{ab} \left(\frac{\phi_e}{\phi_i} \right)^N \left(\frac{1 - \phi_i}{1 - \phi_e} \right)^2, \quad (4)$$

where

k : Apparent permeability [m^2]

k_{ab} : Absolute permeability [m^2]

N : Permeability reduction index (=6) [-].

2.4. Relative Permeability Models Based On MH Core Experiments ^{[11],[12]}

To construct the MH dissociation and consolidation models and to validate the model of permeability–porosity in the MH reservoir during depressurization, we referred to the experimental results ^{[11],[12]}. They performed laboratory experiments to study the MH dissociation, consolidation, and permeability characteristics in a sand-pack which included synthetic MH.

The relative permeabilities for the MH core were also presented by Sakamoto et al. (2009, 2010) ^{[11],[12]} as following equations;

$$k_{rg} = c(1 - S_w^*)^m \quad (5)$$

$$k_{rw} = b(S_w^*)^n \quad (6)$$

where

k_{rg} : Gas relative permeability [-]

k_{rw} : Water relative permeability [-]

c : End point for gas relative permeability [-]

b : End point for water relative permeability [-]

S_w^* : Normalized water saturation [-]

m : Index of gas relative permeability k_{rg} [-]

n : Index of water relative permeability k_{rw} [-].

Equations (5) and (6) were used for the relative permeabilities in the numerical modeling. In the case of high water saturation in the MH core, water is produced selectively and gas remains in the pores owing to capillary pressure. The values of m and n were set as 10 and 3 in Equations (5) and (6), respectively, to indicate that water has higher mobility than gas in regions of high water saturation.

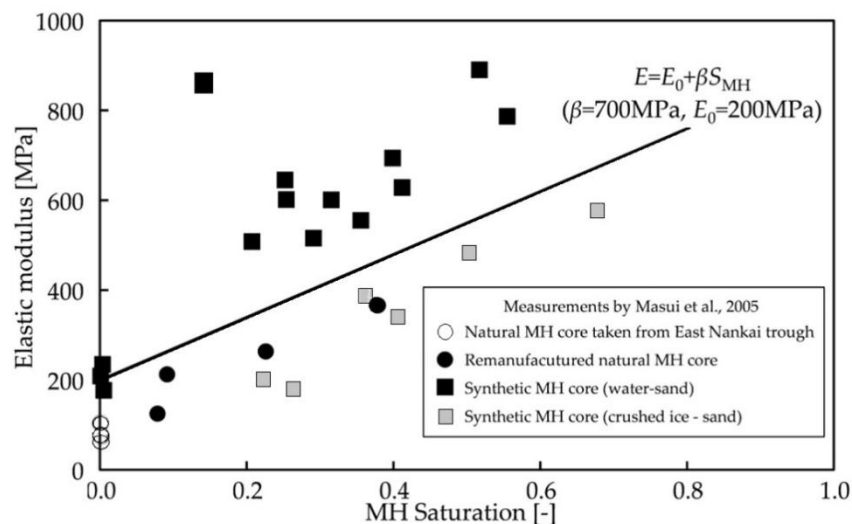


Fig2. Modeling of elastic modules vs. methane-hydrates saturation based on the experimental results of Masui et al.(2005).

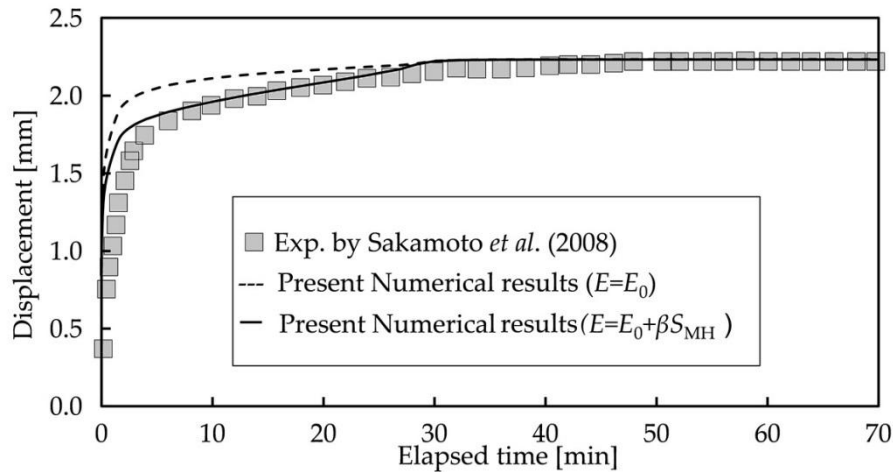


Fig3. Comparison of longitudinal displacements from sand-pack experiment by Sakamoto *et al.*(2009) for depressurizing to 3.3MPa from initial core pressure 10MPa.

2.5. Models of the Elastic Modulus of the Reservoir Matrix

We compared the numerical simulation results with the results of laboratory experiments on MH cores ^{[11],[12]} that evaluated the amount of cumulative methane gas, water production, and displacement during depressurization from an initial core pressure of 10MPa to 3.3MPa. In the simulation case where E was set as a constant $E=200\text{MPa}$, water was produced more rapidly in the early stage after depressurizing than in the experimental results. We expect the compressibility κ or elastic modulus E of the MH reservoir to change with MH saturation because MH increases the elasticity in the reservoir. The value of κ or E must be given as a function of the MH saturation to simulate the correct relative permeabilities calculated using Equations (5) and (6).

As shown in Fig. 2, Masui *et al.*(2005)^[15] presented the relationship between MH saturation and the elastic modulus E based on tri-axial compression tests of MH cores. Their results show that E increases linearly with increasing MH saturation in the core samples. In our study we assume that the elastic modulus and compressibility can be represented by

$$E = E_0 + \beta S_{\text{MH}} \quad (7)$$

where

- E : Elastic modulus of the MH reservoir ($S_{\text{MH}} > 0$) [MPa]
- E_0 : Elastic modulus of sand ($S_{\text{MH}} = 0$) [MPa]
- S_{MH} : MH saturation [-]
- β : Increase rate of elastic modulus vs. S_{MH} [MPa].

Figure 3 shows the numerical results of the displacement behavior using the STARS compared with the experimental results ^{[11],[12]}. In the simulations, a cylindrical coordinate system was used to express the sand-pack core with 31 blocks in the radial direction and 52 blocks in the axial direction (total of 1,612 blocks). Simulations using half and double the number of blocks showed similar results within 0.5% difference in the gas production and displacement values. As shown in Fig.3, the simulated displacement curve at the end of the experiment obtained using Eq. (7) was closer to the experimental results than of the curve based on a constant $E=E_0=200\text{MPa}$.

We also compared our simulation results of temperature distribution with those of Sakamoto *et al.*'s laboratory experiments ^{[11],[12]} to evaluate the numerical model. The temperature distribution in the MH core with variable E showed a better match to the experimental results than that of $E=200\text{MPa}$. Depressurizing of the core pressure from 10 to 3.3MPa led to MH dissociation and endothermic reaction that lowered the temperature from 11-2 °C.

The displacement behavior was calculated by using modified compressibility considering the cohesive strength of MH with a varying initial elastic modulus E_0 of 100–200MPa, Poisson's ratio $\nu = 0.2-0.6$, and increase rate of elastic modulus β of 600–1000MPa, based on the experimental results presented

by Miyazaki et al.(2005)^[16]. The simulation results using $E_0=200\text{MPa}$, $\nu=0.217$, and $\beta=700\text{MPa}$ showed the best match with Sakamoto et al.'s experiments. Therefore, Eq.(7) with $E_0=200\text{MPa}$ and $\beta=700\text{MPa}$, proposed previously, was used to simulate the reservoir consolidation, seabed subsidence, and gas production in our numerical simulations for the hot-water injection method.

2.6. Model of Seabed Subsidence

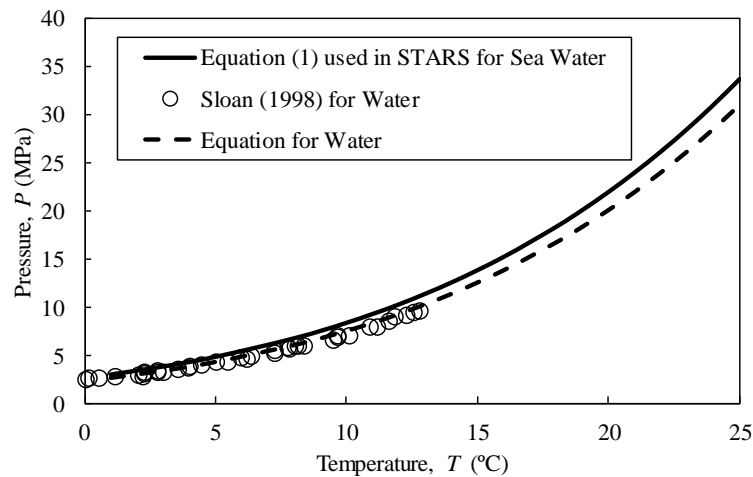
Seabed subsidence is caused by the decreased porosity of the sediment layers and the MH reservoir consolidation. According to Aoki et al. (1991)^[17], we evaluated the amount of seabed subsidence by summing the vertical compaction in a grid at each distance from the seabed to the MH reservoir given by

$$\Delta h = \int \alpha(\phi_i - \phi_v) dz ; \alpha = \exp(-\zeta z) \tag{8}$$

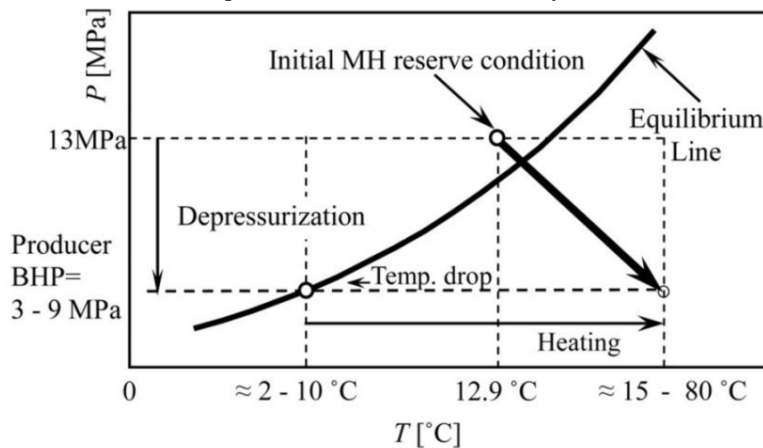
where

- Δh : Displacement of seabed [m]
- z : Distance from seabed [m]
- α : Subsidence ratio [-]
- ζ : Distance index of subsidence [m^{-1}].

The subsidence ratio α , set between 0 and 1, is the contributing ratio of each grid's displacement at z on the seabed subsidence at $z=0$. In the present simulations for the MH reservoir, the distance index of subsidence ratio, ζ in Eq.(8), was set as $\zeta=0.0012\text{m}^{-1}$ that was measured at a dissolved-in-water natural gas field, that has a similar turbidite sedimentary structure with MH reservoirs at the Eastern Nankai Trough (Nishida et al., 1981)^[18]. On the other hand, in the case of the laboratory experiments on sand pack consolidation discussed in the previous section, both values of ζ and α were set as $\zeta=0$ and $\alpha=1.0$, because distance along the z -axis is enough short compared with the size of the MH field.



(a) Equilibrium curve for methane hydrates



(b) Methane-hydrates dissociation conditions

Fig4. Methane-hydrates dissociation conditions on temperature–pressure equilibrium curve by depressurization hot water injection.

2.7. Relative Permeability for a Gas/Water System

To produce gas from the MH reservoir, relative permeability for a gas/water system k_{rw} and k_{rg} vs. water saturation S_w were assumed as shown in Fig. 5. The curves were typical ones for the gas/water system, and authors used for previous study on depressurizing method^{[6], [7]}.

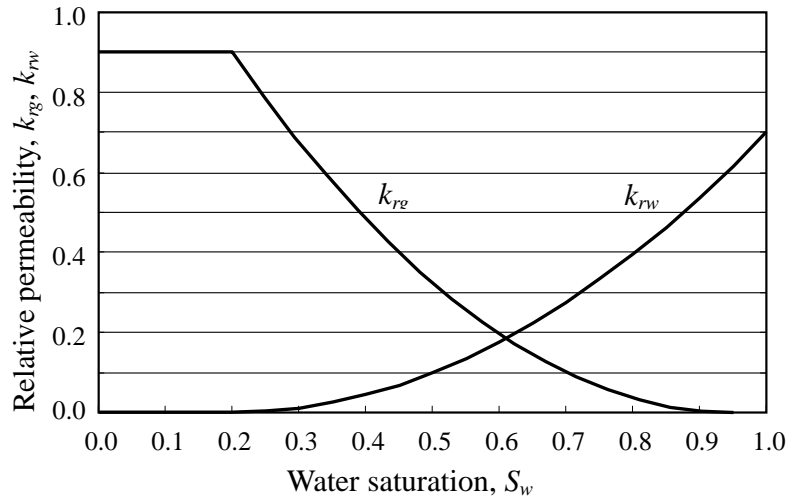


Fig5. Relative permeability curves assumed for gas/water system in MH reservoirs

2.8. Methane-Hydrates Dissociation Model

Figure 4(a) shows the equilibrium curve for methane hydrates formation and deformation used for the simulations (see Sloan (1998)^[19]). As shown in Fig. 4 (b), the pressure–temperature line shows methane-hydrates dissociation conditions by hot water injection shows the MH dissociation when MH reservoir pressure is decreased and hot water is injected into the reservoir. In the hot-water injection method, the heating shifts the reservoir condition (MH temperature and pressure) away from the MH equilibrium line, while in the depressurization method the reservoir condition is on the MH equilibrium line at 2–10 °C and depressurization of 3–9 MPa. Therefore, hot-water injection method is advantageous over the depressurization method as it can control MH reformations at lower temperature region around and in the production well.

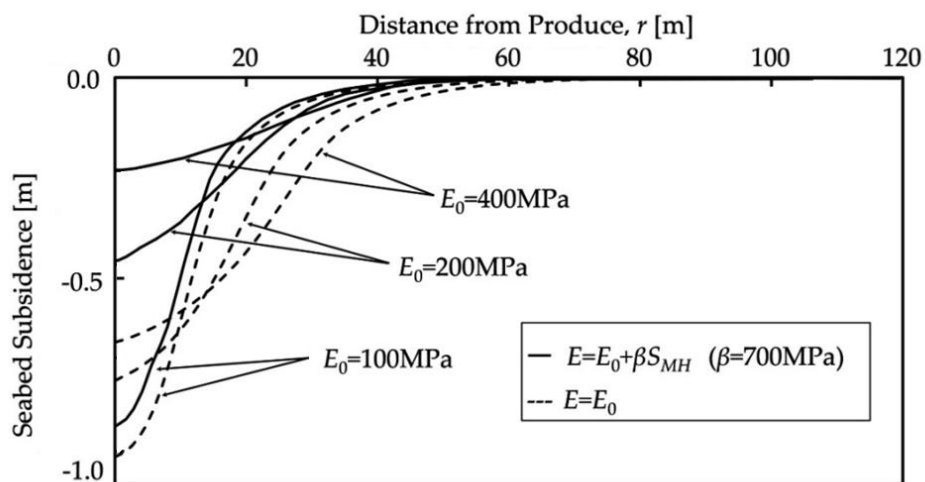


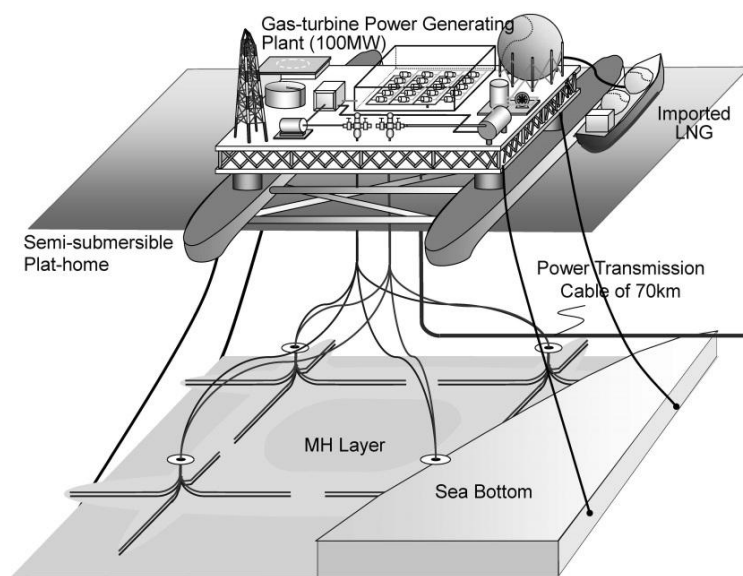
Fig6. Predictions of seabed subsidence at 50 days for different elastic modulus, E_0 . (Initial MH pressure = 13MPa, BHP=3MPa, PDD=10MPa, MH reservoir 15m in thickness)

2.9. Subsidence by Depressurization Method Using a Single Vertical Well

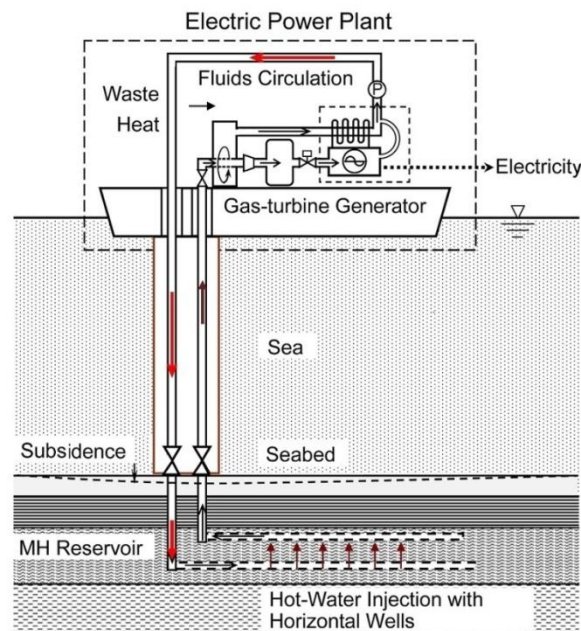
Authors have done numerical simulations on subsidence at seabed by depressurization method using a single vertical well in MH reservoir 15m in thickness and 60% of initial MH saturation(see Fig. 1(a))

with applying the models of the elastic modulus presented at previous sections 2.1 to 2.6 and details of production operations was presented by Matsuda et al.(2016) . Figure 6 shows the simulation results of seabed subsidence for two elastic modulus models expressed by $E=E_0=100 - 400$ MPa and $E=E_0+\beta S_{MH}$; $\beta=700$ MPa and depressurization of 10MPa from initial MH reservoir pressure 3MPa. The maximum subsidence in the results was expected to be about 1m for the soft MH reservoir case with $E_0=100$ MPa that is appeared at the vertical well position. The subsidence is increasing with increasing MH reservoir thickness and decrease of MH saturation from its initial value^[6]. The values show a possibility to induce damages on stability of sedimentary layers above MH reservoir and methane gas leaks to the sea. To avoid this kind of environmental risks, developing an environmentally friendly production method is required to produce gas from a MH layer. Authors have expected that one of the methods is the hot water injection method using a pair of horizontal wells to reduce the seabed subsidence.

3. NUMERICAL SIMULATION OF GAS PRODUCTION BY HOT-WATER INJECTION



(a) Schematic image of the offshore platform



(b) The system of hot water injection and production fluids

Fig7. Integrated system of gas production from MH by hot water injection and a gas turbine electric power generator

3.1. Hot-Water Injection Method Using Dual Horizontal Wells

To produce gas by the depressurization method, relatively high pressure reduction at the producer's bottom-hole pressure is required to maintain a suitable gas production rate from the MH reservoir; however, environmental and safety issues may arise from seabed subsidence induced by sand consolidation. Sasaki et al. (2010, 2014)^{[9],[10]} suggested a more environmentally friendly method based on dissociation heat transfer—the hot-water injection method using dual horizontal wells to control seabed subsidence.

The thermal system of gas production and electric power generation is shown in Fig.7. The system consists of the gas production unit and a power generation plant on a floating platform connected to the hot-water injection system that flows into the MH reservoir. About 40% of the total combustion heat of the produced gas is used to operate the gas turbine power plant, and other 60% becomes waste heat to low temperature sources^[10]. Thus, the system not only generate electricity using the gas produced from the MH reservoir, but also hot water can be generated continuously using the waste heat in the power plant without supplying any additional energy or fuel. The similar concept has been achieved as the co-generation system providing electricity and hot water. A calculation of the heat balance of the system shows that the net heat, which is transferred from the injected hot water generated by the surplus heat, is sufficient for MH dissociation.

In the hot-water injection method, dual horizontal wells are used, similar to the steam assisted gravity drainage (SAGD) method for oil sands (Sasaki et al., 2001)^[20] to carry the injected hot water and the produced gas and water. Following the SAGD method, two wells drilled 5m apart at upper region 2m from its boundary of the MH reservoir are used to create the depressurizing area around the wells at the initial stage, connecting the two wells as shown in Fig.7. However, the vertical distance between horizontal wells can be optimized by thermal conductivity of the reservoir sand and hydrates matrix that is similar to SAGD. The permeability of the MH reservoir between the two wells is improved by MH dissociation around the wells as a result of the depressurizing. Then, hot water is injected from the lower well into the relatively high permeability zone, and the high temperature zone (hot-water chamber) is formed. The hot-water chamber is expanded by MH dissociation by continuously supplying heat to the MH dissociation boundary; therefore, gas production is enhanced through the expansion without plugging by MH reformation in the downstream region.

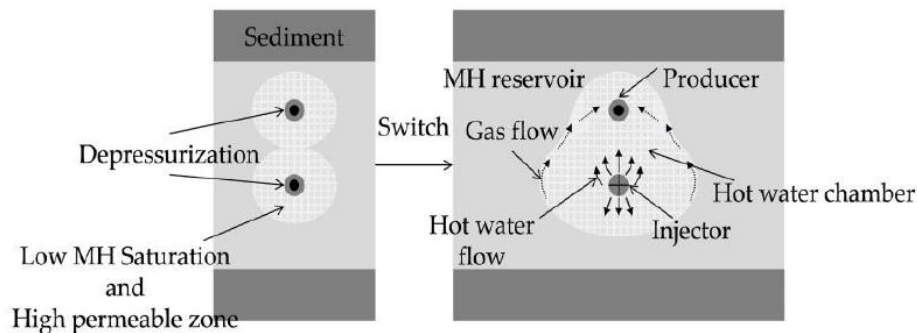


Fig8. Schematic cross section showing hot-water injection and fluids production using dual horizontal wells (Ono et al., 2009)

Table1. Properties of a MH reservoir and conditions of hot-water injection method with bottom-hole pressure control

Area of MH strata	50m×500m
Depth from sea surface	1300[m]
Thickness of MH layer	15 [m]
Initial reservoir pressure	13 [MPa]
Initial temperature	12.85 [°C]
Porosity	40 [%]
Absolute permeability	1000 [md]
Initial MH saturation	60 [%]
Initial water saturation	40 [%]
Hot-water temperature injected	85 [°C]
Hot-water injection rate	500[m ³ /day]
Producer bottom-hole pressure (BHP)	3 to 9 [MPa]

The targeted MH reservoir was modeled as rectangle area of 500m×50m, 15m in thickness and 375,000m³ in volume. Table1 shows the MH reservoir properties and the conditions of hot-water injection with bottom-hole pressure control. In this study, the two horizontal wells500m long are modeled, and assumed to apply depressurization to the MH reservoir with setting the bottom-hole pressure of 4MPafor 90 days to connect the two wells by MH dissociation as shown in Fig. 9. The schematic definition of the model is already presented in Fig. 1(a), and the production system was referred to the SAGD operation. Then, hot-water assuming temperature of 85°Cbased on the analysis of heat balance (see Sasaki et al., 2014) is injected from the lower well into the MH reservoir at a rate of 500m³/day. The numerical simulations were carried out by the STARSTM using 19 blocks in the vertical direction, 15 blocks in the horizontal direction, and 35 blocks in the longitudinal direction along the horizontal wells (total of 9,975 bocks). The gas production rate is not sensitive to the number of blocks used in the calculation, with 1% difference compared with that with 19,950 blocks, because the gas production rate is almost proportional to the injection rate of hot water for the MH dissociation.

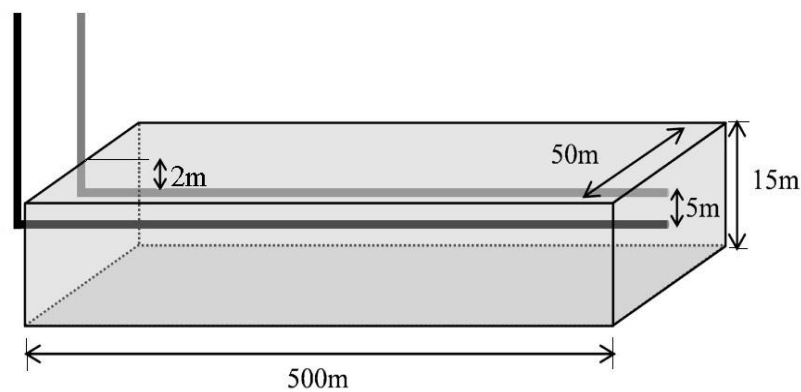


Fig9. Field scale methane-hydrates reservoir model and dual horizontal wells for hot-water injection method (Sasaki et al., 2010)

3.2. Prediction of Gas Production And Seabed Subsidence by the Hot-Water Injection Method

In this study, gas production and consolidation behavior by the hot-water injection method were predicted by numerical simulation, with the bottom-hole pressure of the upper horizontal well set to 3, 6, and 9 MPa.

Figure 10shows a typical simulation result of temperature distribution and fluid flow direction for the hot-water injection method with bottom-hole pressure of 3MPa. The fluid flow to the upper well and the boundary of the MH dissociation zone were confirmed, therefore the MH dissociation zone was expanded.

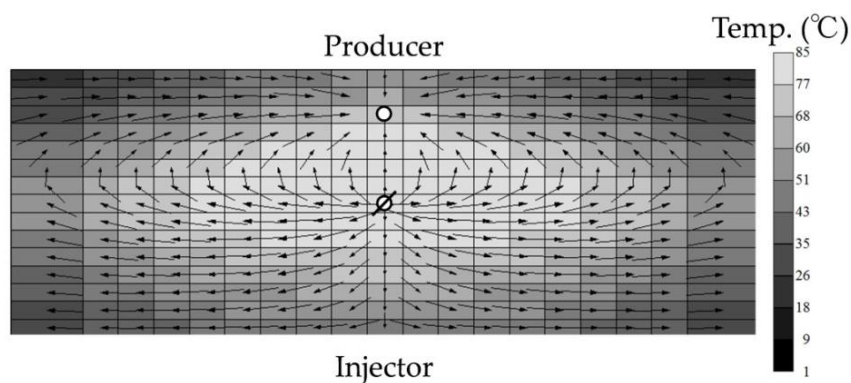


Fig10. Typical simulation result showing temperature distribution and fluid flow direction at 1,825 days by hot-water injection method with bottom-hole pressure of 3 MPa (initial reservoir pressure = 13 MPa)

Figure 11 shows the cumulative gas production simulation results of the depressurization and hot-water injection methods using bottom-hole pressures of 3, 6, and 9 MPa at the upper well from an initial reservoir pressure of 13MPa. The results of the depressurization method were calculated by

continuing depressurization with two horizontal wells after the initial stage of 90 days to clearly demonstrate the effect of hot-water injection. The gas production rate increased with hot-water injection. The cumulative gas recoveries for bottom-hole pressures of 3, 6, and 9 MPa by the hot-water injection method were 1.6, 3.2, and 12.3 times those by the depressurization method, respectively. The cumulative gas production by hot-water injection at a bottom-hole pressure of 9MPa was almost equal to that by the depressurization method at a bottom-hole pressure of 3MPa.

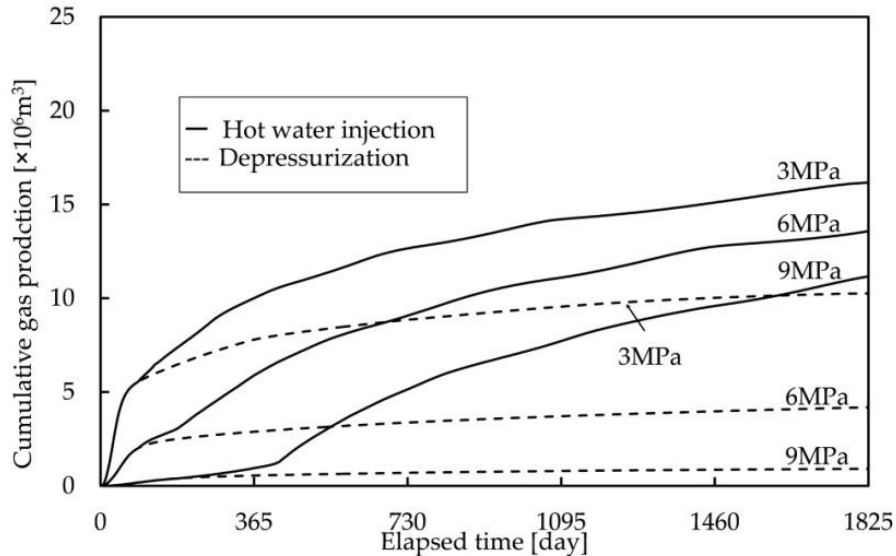


Fig11. Numerical simulation results of cumulative gas production by the depressurization and hot-water injection methods with bottom-hole pressures of 3, 6, and 9 MPa (initial reservoir pressure=13MPa, $\beta=700$ MPa)

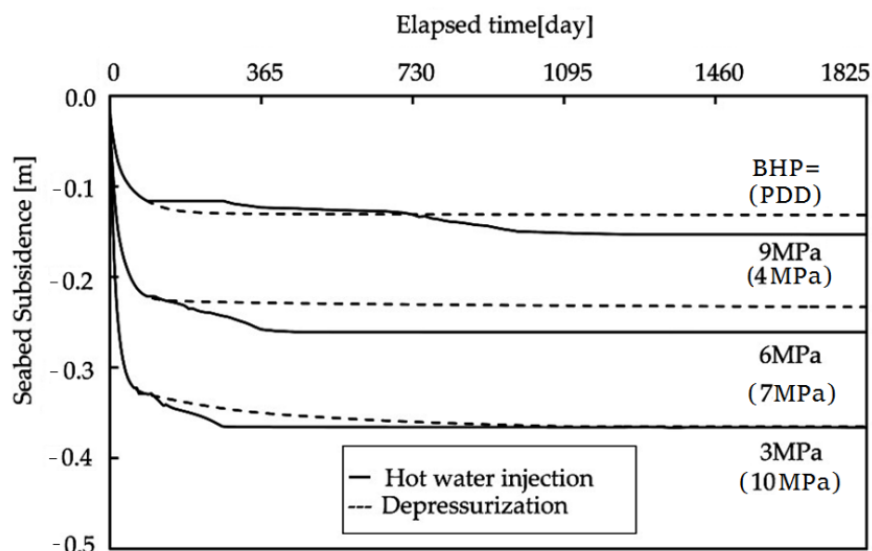


Fig12. Numerical Predictions of seabed subsidence by the depressurization and hot-water injection methods with bottom-hole pressures of 3, 6, and 9 MPa (initial reservoir pressure=13MPa, $\beta=700$ MPa).

Figure12 shows a comparison of the seabed subsidence simulation results of the hot-water injection and depressurization methods for bottom-hole pressures of 3, 6, and 9 MPa. Decreasing the bottom-hole pressure increases the effective stress in the MH reservoir, indicating that the main cause for the increase in cumulative seabed displacement is the decreasing MH reservoir pressure controlled by the bottom-hole pressure. Seabed subsidence by the hot-water injection method shows slightly larger values than the depressurization method, because hot-water injection causes higher MH dissociation and consolidation with less elastic modulus in the MH reservoir as indicated by Eq.(7).

As stated above, the hot-water injection method increases the amount of subsidence compared with the depressurization method for the same bottom-hole pressure. However, for the same amount of cumulative gas production, less pressure drop can be applied at the upper well by injecting hot water,

leading to less seabed subsidence. Thus, higher gas production and less seabed subsidence are expected by using the hot-water injection method. For example, the maximum gas production by hot-water injection with bottom-hole pressure of 9MPa is larger than that by the depressurization method with bottom-hole pressure of 3MPa, and the maximum amount of subsidence is predicted to be about 0.4m, and the gradient of the subsidence is also moderated around center area of the reservoir comparing with about 1m that is simulated by the depressurization method using a single vertical well applying bottom-hole pressure of 3MPa (pressure drawdown; PDD=10MPa)(see Fig. 6 and section 2.9). Thus, the hot-water injection method can make decrease the subsidence and induced tensile or shear stress loaded on the sedimentary rock over the MH reservoir without reducing the gas production rate.

4. CONCLUSIONS

In this study, the consolidation-permeability compound model was applied in numerical simulations of seabed subsidence by gas production from an offshore methane hydrate (MH) reservoir to develop an environmentally friendly gas production method.

To control seafloor displacement, comparative studies of numerical simulations were carried out on gas production and seabed subsidence by applying the hot-water injection methods using dual horizontal wells. The simulation results showed that the cumulative gas production by hot-water injection is expected to be 1.6 to 12.3 times larger than that by the depressurization method with bottom-hole pressures of 3, 6 and 9 MPa. The seabed subsidence is mainly controlled by the MH reservoir pressure affected by the bottom-hole pressure at the upper producer hole. For an equal amount of cumulative gas production, the maximum subsidence by applying the hot-water injection method using 85°C hot water with 500m³/day at a bottom-hole pressure of 9MPa (pressure drawdown of 4MPa) is reduced to about 0.4m from 2m by the depressurization method applying bottom-hole pressure of 3MPa (pressure drawdown; PDD=10MPa).

ACKNOWLEDGMENTS

This study was partly supported by the MH21, Japan National Consortium for Gas Production from MH layer, Japan.

REFERENCES

- [1] Fujii, T., Saeki, T., Kobayashi, T., Inamori, T., Hayashi, M., Takano, O., Takayama, T., Kawasaki, T., Nagakubo, S., Nakamizu, M., and Yokoi, K. (2008). Resource assessment of methane hydrate in the Eastern Nankai Trough, Japan, Offshore Technology Conference, OTC 19310.
- [2] Shankar, U. (2016). Gas hydrate saturation from seismic data constrained by log data in the Krishna-Godavari Basin, J Petrol Explor Prod Technol, 6(1), 13–23.
- [3] Pooladi-Darvish, M. (2004). Gas production from hydrate reservoirs and its modelling. J. Petroleum Technology (JPT), 2004-June, 65-71.
- [4] Masuda, Y., Kurihara, M., and Ohuchi, H. (2002). A field-scale simulation study on gas productivity of formations containing gas hydrates, Proc. of Fourth International Conference on Gas Hydrates (Yokohama),40-46.
- [5] Kurihara, M., Sato, A., Ouchi, H., Narita, H., Masuda, Y., Saeki, T., and Fujii, T. (2009). Prediction of gas productivity from Eastern Nankai Trough methane-hydrate reservoirs, Society of Petroleum Engineers Reservoir Evaluation and Engineering, 12, 477-499.
- [6] Matsuda, H., Yamakawa, T., Sugai, Y., Sasaki, K. (2016). Gas production from offshore methane hydrate layer and seabed subsidence by depressurization method, Engineering, 8-6, 353-364.
- [7] Moridis, G.J., Pooladi-Darvish, M., Santamarina, J. C., Kneafsey, T. J., Rutqvist, J., Reagan, M.T., Sloan, E. D., Sum, A., and Koh, C. (2010). Challenges, uncertainties and issues facing gas production from hydrate deposits in geologic systems, SPE Unconventional Gas Conference (Pittsburgh), SPE-131792-MS.
- [8] Silpngarmlert, S., Ayala H., L.F. and Ertekin, T. (2012). Study of constant-pressure production characteristics of class 1 methane hydrate reservoirs, J Petrol Explor Prod Technol., 2(1), 15-27.
- [9] Sasaki, K., Ono, S., Sugai, Y., Tenma, N., Ebinuma, T. and Narita, H. (2010). Gas production from methane hydrate sediment layer by thermal stimulation with hot water injection, Offshore Technology Conference 2010, OTC-20592-PP.
- [10] Sasaki, K., Sugai, Y., Yamakawa, T. (2014). Integrated thermal gas production from methane hydrate formation. SPE/EAGE European Unconventional Resources Conference and Exhibition (Vienna, Austria), SPE 167780-MS.

- [11] Singh, P., Panda, M, and Sokes, J.P. (2008). Full scale reservoir simulation studies for the east pool of the Barrow gas field and the Walakpa gas field, Petrotechnical Resources of Alaska. DOE Project Number DE-FC26-06NT42962.
- [12] Nimblett, J. and Ruppel, C. (2003). Permeability evolution during the formation of gas hydrates in marine sediments, *J. Geophysical Research*, 108-B9, 2420, doi:10.1029/2001JB001650.
- [13] Sakamoto, Y., Shimogawara, M., Ohga, K., Kumamoto, K., Miyazaki, K., Tenma, N., Komai, T., and Yamaguchi, T. (2009). Numerical study on dissociation of methane hydrate and gas Production behavior in laboratory experiments for depressurization. Part3 - Numerical study on estimation of permeability in methane hydrate reservoir, *International Journal of Offshore and Polar Engineering*, 19-2, 124-134.
- [14] Sakamoto, Y., Komai, T., Miyazaki, K., Tenma, N., Yamaguchi, T. and Zyvoloski, G. (2010). Laboratory-scale experiments of the methane hydrate dissociation process in a porous media and numerical study for the estimation of permeability in methane hydrate reservoir, *Journal of Thermodynamics* 2010. Article ID 452326.
- [15] Masui, A., Haneda, H., Ogata, Y., and Aoki, K. (2005). Effects of methane hydrate formation on shear strength of synthetic methane hydrate sediments, *ISOPE*. I-05-056.
- [16] Miyazaki, K., Masui, A., Yamaguchi, T., Sakamoto, Y., Haneda, H., Ogata, Y. and Aoki, K. (2005) Strain-rate dependency of peak and residual strength of sediment containing synthetic methane hydrate in triaxial compression test. *ISOPE*, Paper - I-09-344.
- [17] Aoki, K., Ogata, Y., and Esaki, T. (1991). On the surface subsidence in natural gas fields, *Proc. 7th ISRM Congress (Aachen)*, *ISRM-7CONGRESS-1991-134*.
- [18] Nishida, T., Saeki, T., Aoki, K. and Kameda, N., 1981. On the surface subsidence in natural gas fields. *Proc. of International Symposium on Weak Rock (Tokyo)*, 701-705.
- [19] Sloan, E. D. (1998). *Clathrate hydrates of natural gases*. 2nd ed., Marcel Dekker, Inc., New York.
- [20] Sasaki, K., Akibayashi, S., Yazawa, N., Doan, Q. Farouq Ali, S.M. (2001). Experimental modeling of the SAGD process- Enhancing SAGD performance with periodic stimulation of the horizontal producer, *SPE Journal*, 6 (1), 89-97.

AUTHORS' BIOGRAPHY



Hiroki Matsuda, has achieved BS and MS degrees in Earth Resources Engineering, Kyushu University, Japan. After the graduation, he joined COSMO Energy Exploration & Production Co., Ltd. as a reservoir engineer from April, 2015.



Takafumi Yamakawa, has achieved BS and MS degrees in Earth Resources Engineering, Kyushu University, Japan. After the graduation, he joined Japan Petroleum Exploration Co., Ltd. (JAPEX) as a petroleum engineer from April, 2012.



Yuichi Sugai, is an associate professor at Kyushu University. Previously, he was with the University more than 10 years. His research interests include experimental and numerical studies on EOR techniques, especially Microbial EOR. He holds MS and PhD degrees from Tohoku University.



Kyuro Sasaki, is a professor of Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Japan since 2005. He holds BS, MS and PhD degrees from Hokkaido University, Sapporo, Japan. His research interests are fluid mechanics and heat & mass transfer phenomena and production methods in Mining and Petroleum Industries.

Citation: *Kyuro Sasaki et al., (2018). Numerical Prediction of Seabed Subsidence with Gas Production from Offshore Methane Hydrates by Hot-Water Injection Method, International Journal of Petroleum and Petrochemical Engineering (IJPPE), 4(1), pp.18-31, DOI: <http://dx.doi.org/10.20431/2454-7980.0401004>*

Copyright: © 2018 Kyuro Sasaki. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited