Development of evaluation technologies for sedimentary characteristics

— Applicability of the technologies to the assessment of methane hydrate sediments —

Norio TENMA

[Translation from *Synthesiology*, Vol.7, No.4, p.228-237 (2014)]

Methane hydrate (MH) is considered to be part of a new generation of energy resources. Depressurization has been proposed as a method of extracting methane gas from MH in marine sediments. During depressurization, sediment deformation may occur because of MH dissociation and increased effective stress. It is therefore important to develop long-term, safe methods for protecting equipment used on the sea floor against the impact of deformation. We have developed the "COTHMA" geo-mechanical simulator to predict sediment deformation during methane gas production from MH. We have also performed laboratory experiments (push-out tests) of well integrity to determine model parameters. Deformation and stress in the vicinity of a production well were evaluated to assess the integrity of the well. Our technologies for evaluating sedimentary characteristics consist of the development of the geo-mechanical simulator and the evaluation of well integrity and wide-area deformation. Based on this research, we are now preparing technologies for practical application.

Keywords : Methane hydrate (MH), MH21 Research Consortium, COTHMA, geo-mechanics

1 Introduction

Methane hydrate (hereinafter MH) is a solid crystal in which the methane molecules are trapped in a basket of water molecules under high-pressure and low-temperature conditions. Environments where these high-pressure and low-temperature conditions exist include the permafrost zone on land and the sedimentary deposit layer at the continental margin in the sea (for example, 200–300 m below the seabed floor at ocean depths of 1,000 m or more). Under such conditions, MH exists in solid form. Lowering the pressure (depressurization) or raising the temperature causes the MH to break down into methane gas and water. Therefore, it has potential as a new natural gas resource. Surveys and research show MH to be present in abundance in the coast of Japan. The Methane Hydrate Resource Development Research Consortium (MH21) was set up in FY 2001 to promote MH resource exploration and development, and R&D is progressing.[1]

The Methane Hydrate Research Center (MHRC) at AIST, which is in charge of development of production methods in MH21, has proposed a depressurization method as an efficient method of gas production.[2] In this method, the pressure is decreased by pumping up water *in situ* from the sediment layer, thereby dissociating the MH into methane gas and water, and then collecting the methane gas. This depressurization method is likely to lead to, the deformation and consolidation of the MH, layer due to its dissociation as shown in Fig. 1. For example, when the sediment deforms while the gas is being produced from the MH layer, local deformation may occur between the production well and the sediment, and this may lead to barriers to production, such as flow path formation or gas leakage. Sediment deformation may also affect the stability of structures such as the well itself, making safe and long-term production difficult to maintain. To enable safe and long-term gas production from the MH layer, it is therefore necessary to develop evaluation technologies, such as a numerical simulator, that are able to predict sediment deformation behavior.

However, the basic characteristics that must be handled in a numerical simulator such as "How do mechanical characteristics of the MH layer change during the dissociation process?" and "What role does MH play mechanically?" were not known at the start of the project, so we were unable to evaluate sediment deformation and consolidation. Therefore, "evaluation technologies for sedimentary characteristics" is being developed as a technology for safe and long-term gas production. As shown in Fig. 2, this technology is one of the developmental aims of gas production technology from the MH layer that will be explained below; MHRC conducts R&D as the main administrator of this area. The author is engaged in the development of evaluation technologies for sedimentary characteristics as the Deputy Director (also the Team Leader of Reservoir Simulator Team) of MHRC. The Reservoir Simulator Team is composed of a total of 14 people, including three researchers and technical staff, to develop evaluation technologies for sedimentary characteristics. The author is responsible for overall team management and the

Methane Hydrate Research Center, AIST Tsukuba West, 16-1 Onogawa, Tsukuba 305-8569, Japan
∗ E-mail: tenma-n@aist.go.jp

Original manuscript received January 14, 2014, Revisions received August 25, 2014, Accepted August 28, 2014

systematization of research. In this paper, I will discuss the progress made in evaluation technologies for sedimentary characteristics, concentrating on the topics handled by the Reservoir Simulator Team.

2 The work of the Methane Hydrate Resource Development Research Consortium (MH21)

In the Phase 1 period of FY 2001 to 2008, MH21 yielded many results, such as the calculation of the resource assessment for methane gas in the MH layer in Eastern Nankai Trough region and the successful continuous production by depressurization method in the onshore production test at Canada. Phase 2 was launched in April 2009, with a scheduled completion date in FY 2015, "for evaluating at high reliability the potential for the methane gas in the MH layer to be used as an energy resource and for identifying the technological challenges necessary to organize the technologies for commercial development of

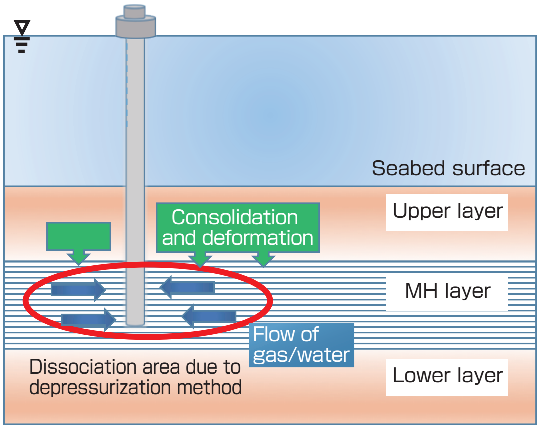


Fig. 1 Mechanical behavior of the MH layer
It is predicted that sediment deformation will occur by the MH dissociation and consolidation during the depressurization operation.

the MH layer, through R&D such as the offshore production test in the coast of Japan." In Phase 2, Associate Professor Yoshihiro Masuda of the University of Tokyo was appointed the Project Leader. The R&D is being conducted by the Research Group for Field Development Technology, the Research Group for Production Method and Modeling, the Research Group for Resource Assessment, and the Group of Administrative Coordination in MH21. In March 2013, the first offshore production test was conducted for the first time in the world in the Daini Atsumi Knoll of the Eastern Nankai Trough. This test was conducted: (1) to demonstrate that gas can be produced from hydrates by the depressurization method and to confirm gas productivity, and (2) to establish the technology needed to apply the depressurization method at relatively shallow depths below the seabed floor. About 120,000 m^3 of gas was produced in six days using the depressurization method. Valuable data was also obtained for reservoir evaluation. Based on the data obtained in this field test, various research groups and teams are currently collaborating and conducting detailed investigations into the diverse phenomena of the MH layer.

Similar research is in progress around the world, such as in the United States, Korea, China, and India. For example, Korea is engaging in a gas hydrate survey in the Tsushima Basin, and the US is surveying reserves, along with the earthquake exploration surveys, in the Gulf of Mexico,[3] however, no offshore production tests have yet been conducted.

As the administrator of the Research Group for Production Method and Modeling, MHRC engages in R&D for various production methods, including the depressurization method.[4] In Phase 1, several production methods, including depressurization and heating methods, were investigated. The depressurization

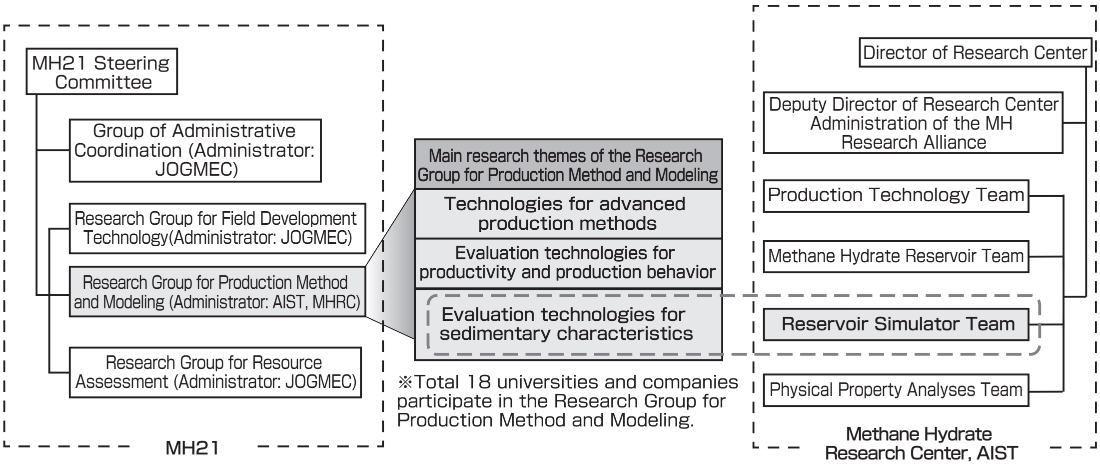


Fig. 2 Relationship between the Research Group for Production Method and Modeling and the Reservoir Simulator Team, and research themes
In the Methane Hydrate Resource Development Research Consortium (MH21), the Methane Hydrate Research Center (MHRC) oversees the R&D as the administrator of the Research Group for Production Method and Modeling. The Reservoir Simulator Team engages in the development of evaluation technologies for sedimentary characteristics as a research team within the MHRC.

method was proposed for reasons of its energy efficiency. In Phase 2, the depressurization method is being applied to further develop the complex production method (combined method) to stably produce large volumes of methane gas, to improve the production simulator (MH21-HYDRES) by looking at how closely its predictions match the actual production tests, and to evaluate wide-area sediment deformation that takes place during methane gas production. Specifically, methods of obtaining a high productivity and recovery rate are being developed as "technologies for advanced production methods," and long-term, stable production is attempted through the development of quantitative analysis and numerical models of the production impediment factors such as sand problems, skin formation, fine-grain sand accumulation, decreased permeability due to compression, or flow blockages that occur during MH reformation, as well as the development of technologies to control and counter such impediments. We also engage in research into "evaluation technologies for productivity and production behavior" with the aim of developing a practical simulator by increasing the accuracy of the production simulator, through the development of a reservoir model to which the discontinuity and heterogeneity of the reservoir are introduced as parameters, and its degree of matching with laboratory experiments. Research on "evaluation technologies for sedimentary characteristics" is also being done to guarantee the long-term safety of the sediment deformation and consolidation behavior due to methane gas production from the MH layer.

3 Evaluation technologies for sedimentary characteristic

Since sediment deformation accompanying gas production from the MH layer is predicted, the development of technology that ensures safe and secure production in the development areas over the long-term is important for reasons of social and legal acceptability. This is particularly true for the development areas as shown in Fig. 3, in which it is necessary to evaluate the effects of fault discontinuity

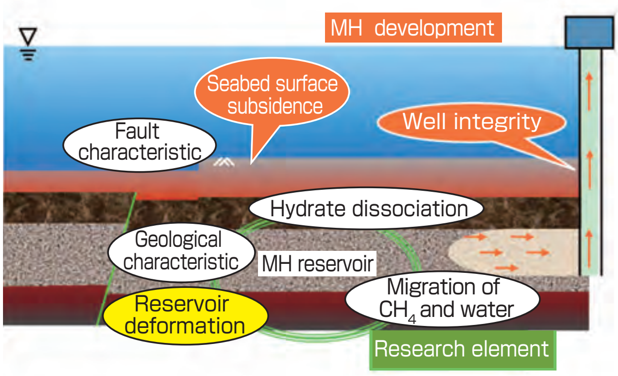


Fig. 3 Development of evaluation technologies for sedimentary characteristics in the MH development
To establish a long-term, safe, and secure production method, it is necessary to solve various issues on sedimentary characteristics.

and sediment heterogeneity on seabed floor subsidence or sediment deformation, along with deformation behavior within the MH layer. It is also necessary to analyze the changes in deformation and strength of the sediment from the early stage of development to be able to evaluate the long-term effects through comparison of factors before development to after well abandonment. Moreover, since there will be large stress differences in the well during the application of the depressurization method, it is necessary to analyze the stress on the well and to evaluate well integrity throughout the production period. To solve these issues through "sedimentary characteristic evaluation technology," the Research Group for Production Method and Modeling is engaged in: (1) development of a geo-mechanical simulator, (2) evaluation of well integrity, and (3) evaluation of wide-area deformation, on which the R&D is being carried out in collaboration with private companies and universities within the MH21 framework.

Specifically, for (1) the development of the geo-mechanical simulator, the COTHMA, which will be explained later, is being developed. Various mechanical parameters of the MH layer are also being collected to enable the assessment of the deformation and compression behavior of the MH in the simulator.

In (2), the evaluation of well integrity, the sediment deformation and stress distribution in the vicinity of the production well during the application of the depressurization method are analyzed and evaluated based on the geo-mechanical simulator. Physical properties of wells for well integrity estimation are also being collected.

Moreover, in (3) evaluation of wide-area deformation, the method of analyzing the effects of discontinuities such as faults and sediment heterogeneity on seabed floor subsidence or sediment deformation are being surveyed and investigated; and sensitivity analysis using the simulator is being carried out. The sediment deformation and change in strength during the period from start of development to well abandonment are analyzed, and the long-term effect of development is evaluated by comparison with the situation before MH development. These subjects are interrelated as shown in Fig. 4. The goal is to develop a "geo-mechanical simulator" that combines the knowledge of "evaluation of well integrity" with "evaluation of wide-area deformation" (which will be explained below), and ultimately to provide various information necessary to plan the MH development.

With the framework of MH21, the Reservoir Simulator Team of MHRC collects mechanical parameters through laboratory experiments for (1) the development and advancement of the geo-mechanical simulator, and applies integrated evaluation of the mechanical characteristics of the deep-water unconsolidated deposit layer that is unique to MH development. It also engages in (2) the evaluation of well stability by looking at the stress distribution in the vicinity of wells during the application of the depressurization method.

In the following section, details will be given on the outline and calculations of the geo-mechanical simulator that the Reservoir Simulator Team is currently developing, the research on the contact surface characteristic conducted as part of well integrity, and the evaluation of wide-area deformation conducted through collaboration with private companies and universities within the MH21 framework.

3.1 Development of the geo-mechanical simulator

For the numerical analysis of sediment deformation, development and use are pursued in the fields of civil engineering and architecture. Normally, laboratory experiments are conducted using on-site cores to collect parameters such as the elastic modulus that reveals how much the sediment deforms with pressure. The stress distribution and the amount of strain within the sediment layer are then calculated using the finite element method (FEM) using these parameters.[5] However, in gas production from the MH layer, the MH that is originally present in the layer in solid form dissociates into water and methane gas by the depressurization method, and the stress distribution in the layer changes as the MH that previously existed in solid form disappears. Moreover, the gas and liquid that are produced by dissociation can move through the sedimentary layers. Since MH dissociation is an endothermic reaction, heat exchange takes place within the layer. Therefore, unlike with general sediment deformation, it is not possible to analyze the sediment deformation behavior in MH development until the simulator can handle the mechanical parameters for the elastic modulus and strength of the MH bearing sand sediment, the flow of gas and liquid in the layer, and the changes in temperature due to the dissociation and formation of MH. Therefore, jointly with West Japan Engineering Consultants, Inc. (WJEC) which has experience in numerical simulation and analysis of sediment deformation, a geo-mechanical simulator for MH bearing sand sediment was developed by adding functions for multi-phase flow analysis, heat conduction analysis, and MH dissociation and formation, to the sediment deformation numerical simulator.[6][7] The handling of mechanical MH parameters, which will be explained below, and the basic design of the numerical simulator were conducted mainly by the Reservoir Simulator Team. Currently, it has become a FEM with combined functions for stress, multi-phase flow, heat conduction, MH dissociation/formation, among others. The simulator is called the “Coupled Thermo-Hydro-Mechanical Analysis with Dissociation and Formation of Methane Hydrate in Deformation of Multiphase Porous Media” (COTHMA). Recently, deformation simulators with functions similar to COTHMA have been proposed,[8][9] but as it will be explained later, COTHMA was developed based on the laboratory experiment results from core samples of MH bearing sand sediments. It is a simulator that can most accurately represent the mechanical behavior of MH bearing sand sediments. The following are the characteristic functions of COTHMA that is under development and improvement.

1) Analysis of complex processes in multiple phases (vapor, liquid, and solid).

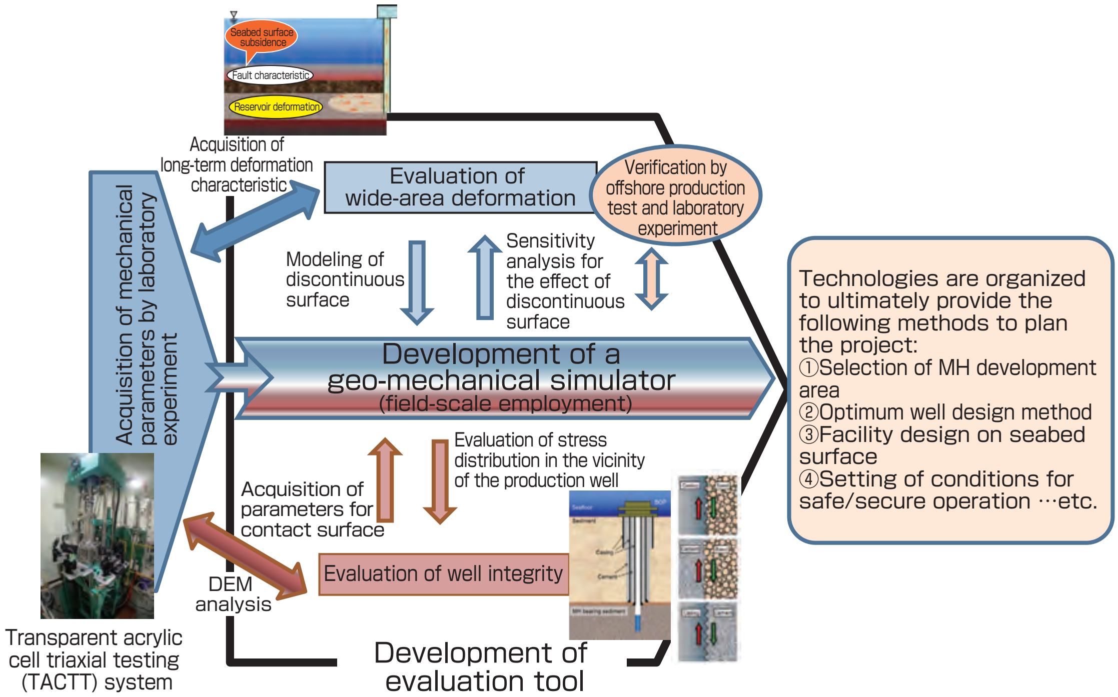
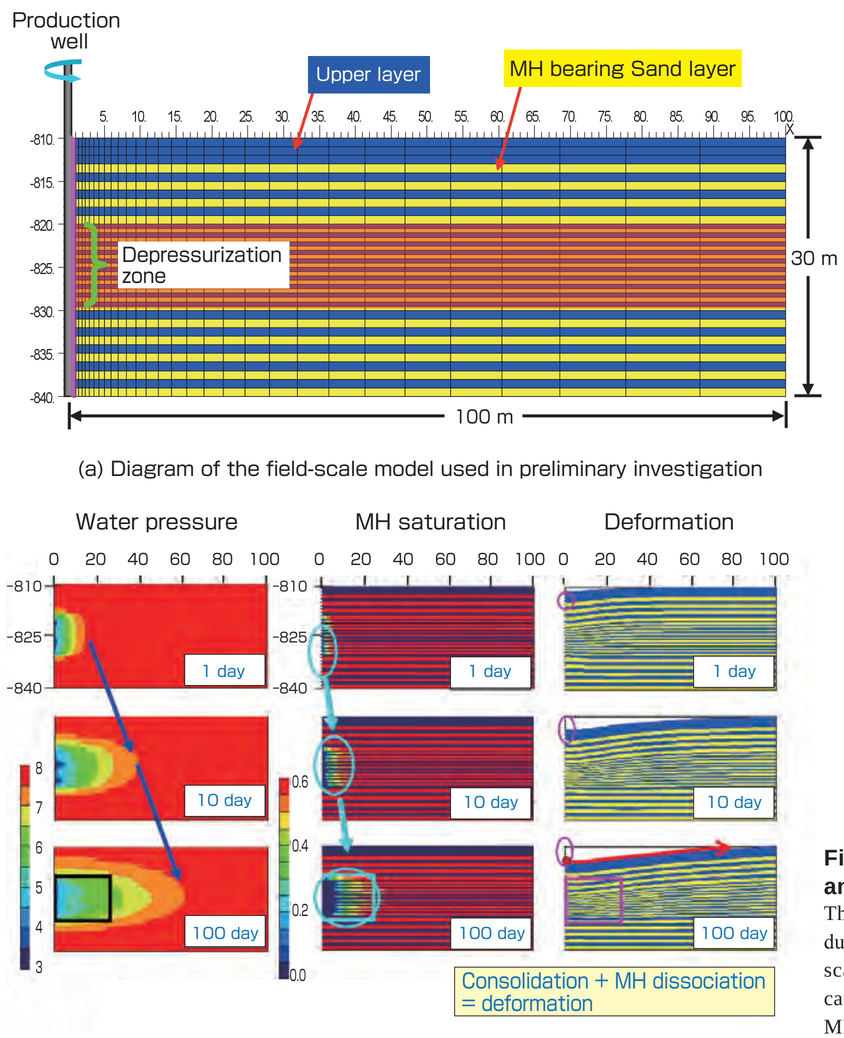


Fig. 4 Development of evaluation tool for sedimentary characteristics

Tools are developed while integrating the results of the evaluations of well integrity and wide-area deformation that are currently being done.

2) Application for various production methods (depressurization method, thermal recovery method, and combined method) to extract methane gas from MH sediment.
3) Treatment of MH dissociation/re-formation.
4) Treatment of ice solidification/melting.

So far, reproduction of the laboratory experiment results has been carried out to validate the simulator.[10][11] Various sensitivity analyses were conducted on a field scale using this simulator.[12] Figure 5 shows an example of predictive investigation conducted using the simulator on a field scale.[13] The model used is an axisymmetric model of the 2D cylindrical coordinate system, with the well as the central axis. The right-half region of the well is broken down into its elements. In this model, there is a MH layer sandwiched between mud layers. A simple model is assumed for the MH layer of alternating sand-mud layers, based on field surveys. Specifically, the thickness is set at 1 m each of alternating sand and mud. The calculation is done assuming that depressurization takes place in the section in which the well reaches the MH layer. The contour diagram of water pressure, MH saturation, and deformation of 1 day, 10 days, and 100 days after the start of the operation of depressurization are shown. As it can be seen from the water pressure change, the area with decreased water pressure in the vicinity of the depressurization zone spreads after the start of depressurization. The low-pressure area spreads by the depressurization method, and the MH dissociation area spreads in the sand layer corresponding to such areas. The effect of deformation by MH dissociation and consolidation can be seen in the sand layer. As the MH dissociation area spreads, the overall deformation of the alternating sand-mud layers progresses. Particularly, the effects caused by consolidation and MH dissociation coexist in the deformation, and the effect manifests in a greater area than the dissociation area. However, the calculations show that the subsidence gradually decreases and that the area in the vicinity of the well stabilizes after a certain degree of subsidence. Since the effects of MH dissociation can be seen, the deformation is thought to be greater than the consolidation deformation of the layer, but it appears that the deformation gradually subsides, since the structure within the sand layer is maintained to some degree, even after dissociation of the MH. Our current numerical model is constructed based on the knowledge of sensitivity analyses and the information from the first offshore production



(a) Diagram of the field-scale model used in preliminary investigation

(b) Contour diagram of calculation result (water pressure, MH saturation, deformation)

Fig. 5 Example of field-scale sensitivity analysis result
This is a contour map that investigates the deformation during the operation of depressurization using the field-scale simplified model. The effects of deformation caused by MH dissociation and consolidation of the MH layer are shown.
※Deformation values of the contour map are expressed at 30 times the calculated values.

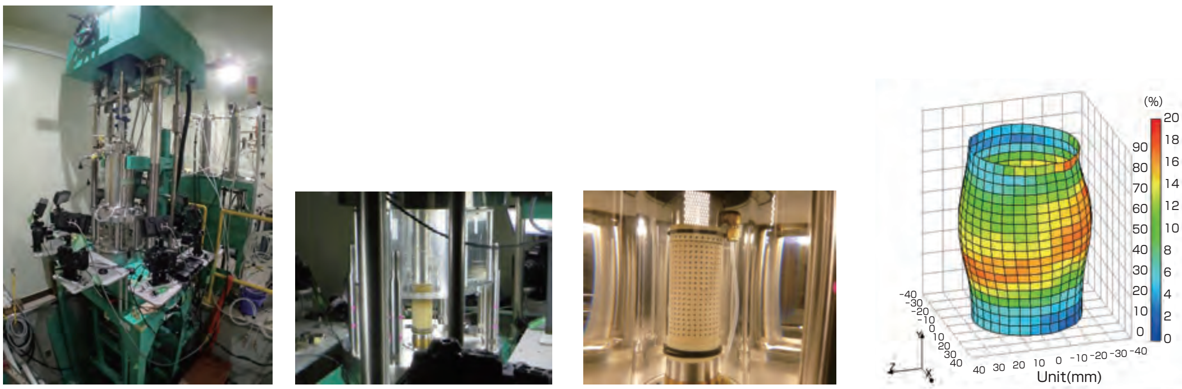
test. Analysis and evaluation continues for the deformation behavior during gas production.

Parameters such as elastic modulus and strength (peak value of stress) of the MH-bearing sand sediments had never been measured, and it was impossible to obtain a core sample of the MH layer. It was therefore necessary to prepare samples and develop a testing device specifically for MH to obtain these parameters. The ways to make the artificial MH specimens were investigated by collaborating with universities and private companies utilizing the MH21 framework. We established a way to make such specimens by injecting the gas into a frozen sand specimen and then melting it at a certain pressure and temperature. We succeeded in redesigning and developing a triaxial testing device, originally designed for use in conventional soil studies, to handle the artificial specimens. This enabled laboratory experiments to be carried out on MH. As part of the R&D of MH21, basic boring was conducted in the Tokai-oki to Kumano-nada area from late-January to mid-May 2004. Natural MH core samples were obtained successfully. The elastic modulus and strength values for the MH core were obtained by conducting laboratory experiments on this natural MH core and artificial specimen. It was found that the elastic modulus and strength increased as the MH saturation ratio (volume ratio of MH in the pore) increased.[14]-[18] The experimental equation was derived based on laboratory experiments results and incorporated into the geo-mechanical simulator. This enabled the analysis of the mechanical behavior of the MH layer.

We recently succeeded in obtaining a pressure core (a core in which a high pressure condition is maintained to prevent MH dissociation) at the offshore production test site in the summer of 2012. These cores are managed and stored at AIST Hokkaido. Detailed data analysis of the cores from the MH layer is now being carried out. Moreover, to obtain accurate parameters for MH cores, a "transparent acrylic cell triaxial testing (TACTT) system" that allows laboratory experiments to be carried out while maintaining high pressure (Photo 1) was adopted for conducting the tests.[19] The chief characteristic of this device is that the natural core, collected with maintained high pressure, can be transferred to the device without loss of pressure; a sufficient confining pressure is applied through the rubber sleeve to conduct the triaxial test. The sample cell section is made by acrylic to enable visual observation of the triaxial test under high pressure. These techniques made it possible to gain an understanding of the local deformation of the core during the test. Visual observation could be made of the sheared section when stress was applied to the layer, and local deformation and strain could thus be quantified. This device contributes to improvement of the precision of the parameters used in the geo-mechanical simulator.

3.2 Evaluation of well integrity

We are working on evaluation of well integrity using the geo-mechanical simulator that is under development. For example, it is becoming apparent that the stress distribution vicinity production well varies according to the difference of depressurization rate (which means the period of decreasing pressure from hydrostatic pressure to 3 MPa at the bottom of the borehole).[20] To further improve precision of analysis, it is necessary to match the well model closely to the condition at the actual site. Wells are composed of numerous and complex materials, including the casing, cement, and sedimentary layers, and it is particularly important to understand the strength of the contact surfaces of these materials. However, there has not been much research on the contact surfaces of wells in deep-water or large depth conditions as seen in the case of MH layers. We are therefore conducting push-out tests to obtain these parameters in order to establish a well model that matches the actual site. Photograph 2 shows a sample



(a)Overview of the apparatus (b)Sample cell section of the apparatus (c)Photographing the sample (d)Example of image analysis

Photograph 1. Transparent acrylic cell triaxial testing (TACTT) system

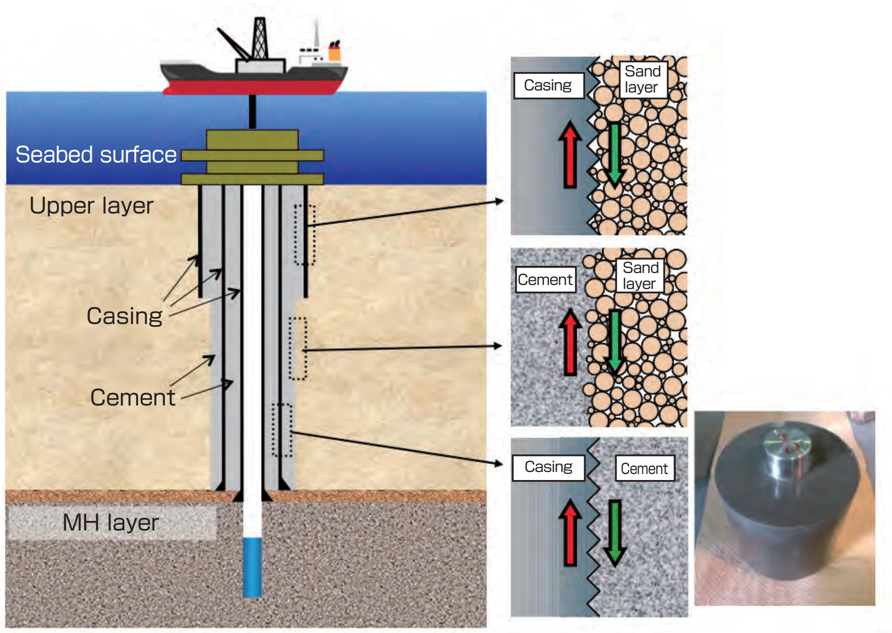
(a) Overview of the apparatus, (b) sample cell section of the apparatus, (c) photographing the sample, and (d) example of image analysis. As it can be seen from the apparatus overview, the image can be obtained from multiple directions at the sample cell section, and the changes in the sample surface can be observed using the image data.[19]

prepared to obtain the contact surface strength between the casing and cement. The steel rod is placed in the hollow sample made of cement, and data on contact surface strength between the materials is collected by conducting the push-out test in which the rod is pushed through. So far, experiments on the contact surface strengths of casing-sediment, casing-cement, and cement-sediment have been conducted. For example, for the contact surface strength of casing-cement, we derived an experimental equation using the effective confining pressure among others as parameters.[21][22] In the future, we plan to conduct further sensitivity analyses using experimental equations such as this, and to propose a method for the well design of MH development.

At the contact surface, local deformations by particle crushing may occur, but it is difficult to understand the details of the local effect in the push-out test due to the settings of experimental conditions and experiment time. Therefore, investigation using the distinct element method (DEM) is carried out for evaluation by numerical analysis. Since the DEM is a method that tracks the motions of multiple particles, it is possible to quantitatively evaluate the micro-mechanical quantities that cannot be measured experimentally. Since it is known that the “roughness” of the contact surface is related to strength, we are attempting to systematize the unevenness of the well surfaces or sand particles at various scales of roughness using the DEM. By gaining a systematic understanding of the properties of the contact surface under various mechanical conditions by DEM, we hope to elucidate the mechanical behavior of the contact surface and its modeling.[23]

3.3 Evaluation of wide-area deformation

In development for practical use of MH, it is thought that long-term production may not be possible because depressurization cannot be maintained in cases where there are discontinuities such as faults in areas surrounding the points of MH development, as faults may become flow-paths as shown in Fig. 3. We are therefore investigating a way of evaluating the effects of discontinuous surfaces. In MH development, there is a risk that deformation behavior such as consolidation before, during, and after production may change greatly when using the depressurization method. This prompted us to investigate sediment characteristics over the long-term. The following two research studies are being conducted for evaluation of wide-area deformation. First, for the purpose of establishing a method of selecting MH development areas, we created a numerical model based on the Eastern Nankai Trough, and investigated the effect of sediment layer heterogeneity and fault discontinuity by including the presence of faults in the numerical model. Specifically, by comparing and investigating the mechanical behavior when the depressurization method is applied in the numerical model with and without faults, it is possible to understand the effect of discontinuities, such as faults, on the mechanical behavior. Sensitivity analysis is then conducted to understand the conditions under which the sediment layer condition is optimal for the MH development area. This type of location is then selected as the MH development area. The parameters of sensitivity analysis considered so far include the distance between well and fault, the dip angle of the fault, and whether the fault is normal or a reverse fault.[24] The results of the sensitivity analysis so far confirm that the deformation behavior changes at the



Photograph 2. Sample for measuring the contact surface strength between the casing and cement (part of the diagram has been modified)[21]

Since the well is a combination of complex materials of casing, cement, and sedimentary layers, push-out tests were conducted by preparing various samples with combinations of different materials.

fault during the depressurization operation. In the future, we plan to systematize the effects of sediment deformation on each parameter and establish a way of selecting sites that are suitable for MH development.

We also analyzed the sediment deformation and strength change during the period from start of MH development to well abandonment, and evaluated the long-term effects of MH development by comparing the situation before and after MH development. Specifically, using the artificial MH specimen made in the particle size distribution obtained from exploratory drillings of the MH layers, the triaxial test is conducted under the conditions assumed for the situation before and after gas production. During the application of the depressurization method (i.e., during production) and during the recovery of water pressure after the stop of the depressurization operation (i.e., after production), the liquid pressure in the layer changes, and therefore the deformation strength characteristics before and after gas production can be understood by conducting tests in which the liquid pressure in the pore of the artificial specimens is varied.[25] In the future, we plan to further develop a constitutive equation using the deformation strength obtained from the laboratory experiments, and to embark on long-term sediment deformation analysis by incorporating such equations into the geo-mechanical simulator.

4 On future R&D

The “Basic Plan on the Ocean Policy” which was approved by the Cabinet on April 26, 2013, contains the following statement: “The preparation of technology shall be conducted to achieve commercialization with FY 2018 as the goal, taking into account the results of the offshore production test, to make MH, which appears to be abundantly present in the coast of Japan, a future energy resource. In doing so, technological development will be promoted such that projects for commercialization led by private companies can commence in the latter half of 2018, taking into account the international situation.” Following the “Basic Plan on the Ocean Policy,” the “Plan for the Development of Marine Energy and Mineral Resources” is currently under revision. And it is thought that the long-term, stable production technology will be promoted. It is necessary to continue steady research for the evaluation technologies for sedimentary characteristics in the future.

Currently, a 3D model has been constructed and is being updated based on the results of core analysis obtained in the field test site. Analysis and evaluation of the mechanical behavior of the MH layer are being carried out through the investigation of offshore production test. We plan to continue improving the geo-mechanical simulator through such investigations. The world’s largest laboratory experiment apparatus, the High-pressure Giant Unit for Methane Hydrate Analysis (HiGUMA) for the MH layer is set up at AIST Hokkaido.[26] This is a device for evaluating the behavior of gas production and MH layer dissociation that cannot be understood by merely using core-scale laboratory experiments when the depressurization method is applied. Using this apparatus, we are attempting to measure the deformation behavior in the vicinity of wells during the depressurization operation. We hope to measure the deformation behavior when the depressurization method is applied, and to improve the precision of the geo-mechanical simulator through experimental verification.

By continuing the simulator development combining functions such as the MH development selection method established by evaluations for wide-area deformation evaluation and for well vicinity as mentioned in subchapters 3.2 and 3.3, we ultimately wish to develop a tool that contributes to the MH development area selection, the optimum well design method, and the design of equipment used on the seabed floor for gas production from the MH layer.

5 Conclusion

In this paper, we discussed the “evaluation technologies for sedimentary characteristics” as follows: (1) the development of a geo-mechanical simulator, (2) the evaluation of well integrity, (3) the evaluation of wide-area deformation, and outline, result, and future development policy of this theme.

The proposal of a long-term, stable production technology for the future is important for the practical realization of MH development. The viewpoint of evaluation technology in terms of mechanical characteristics is the core technology. Our research so far, we believe, has achieved major success in the form of our numerical simulator that can help understand the mechanical characteristics of the MH layer and can handle the mechanical behavior of MH, through obtainment of the natural MH core that is the research subject, establishment of ways to make the artificial specimen, and comparison with the results of laboratory experiments using the natural MH core.

Verification of the results of the first offshore production test was also conducted through industry-academia-government collaboration based on the MH21 framework. These research activities also assisted the training of human resources for MH development. The development of various experimental apparatuses has also been accomplished through this research. By gaining a further understanding of the mechanical characteristics of the MH layer and by the improvement of the geo-mechanical simulator, we hope to apply the “evaluation technologies for sedimentary characteristics” to actual sites of gas production from MH sediments.

Acknowledgements

This study was financially supported by the Research Consortium for Methane Hydrate Resources in Japan (MH21 Research Consortium) in the Japan research. By further understanding the mechanical y to continue mechanical behavior. In this paper, I am thankful to the members of the Reservoir Simulator Team, including researchers Dr. Jun Yoneda, Dr. Jun Katagiri, and Dr. Kuniyuki Miyazaki, as well as the people of MH21.

References

[1] MH21 Research Consortium, http://www.mh21japan.gr.jp/english

[2] M. Kurihara, A. Sato, H, Ouchi, H. Narita, Y. Masuda, T. Saeki and T. Fujii: Prediction of gas productivity from Eastern Nankai Trough methane-hydrate reservoirs, *SPE Journal*, 125481-PA, (2009).

[3] U.S. DOE: Fire in the Ice, *Methane Hydrate Newsletter*, 13 (2), (2013).

[4] J. Nagao: Development of methane hydrate production method –A large-scale laboratory reactor for methane hydrate production tests–, *Synthesiology*, 5 (2), 89-97 (2012).

[5] A. Fukada, M. Nakano, Y. Kawamura and T. Matsuda: LNG chika tanku shuhen morido no jishinji chinka yosoku kaiseki (Subsidence prediction analysis during earthquakes of the earth embankment around the underground LNG tanks), *Proc. 57th JSCE Annual Conf.*, 1087-1088 (2002) (in Japanese).

[6] K. Aoki, Y. Ogata, A. Masui, J. Mori and K. Hou: Land subsidence due to development of Methane Hydrate, *Proc. 2003 MMIJ* (A/B), 235-236 (2003) (in Japanese).

[7] K. Aoki, Y. Ogata, A. Masui, J. Mori and K. Hou: Numerical analysis of land subsidence due to development of Methane Hydrate, *Proc. 2006 MMIJ* (Fukuoka), (2006) (in Japanese).

[8] M.Y.A. Ng, A. Klar and K. Soga: Coupled soil deformation-flow-thermal analysis of methane production in layered methane hydrate soils, *Proc. 2008 Offshore Technol. Conf.*, OTC19364, (2008).

[9] S. Kimoto, F. Oka and T. Fushita: A chemo-thermo-mechanically coupled analysis of ground deformation induced by gas hydrate dissociation, *Int. J. of Mechanical Sciences*, 52 (2), 365-376 (2010).

[10] Y. Sakamoto, M. Kakumoto, K. Miyazaki, N. Tenma, T. Komai, K. Aoki and T. Yamaguchi: Numerical study on consolidation and gas production behavior in a laboratory-scale experiment for dissociation process of methane hydrate by depressurization: Estimation of permeability in methane hydrate reservoir, Part 7, *Journal of MMIJ*, 126 (12), 631-639 (2010) (in Japanese).

[11] K. Miyazaki, Y. Sakamoto, M. Kakumoto, N. Tenma, K. Aoki and T. Yamaguchi: Triaxial compressive properties of artificial methane-hydrate-bearing sediments containing fine fraction, *Journal of MMIJ*, 127 (9), 565-576 (2011) (in Japanese).

[12] J. Yoneda, K. Miyazaki, N. Tenma and M. Hyodo: Prediction of long-term stratal deformation resulting from depressurization for methane hydrate extraction, *Proc. 13th Japan Symposium on Rock Mechanics*, CD-ROM, JSRM-64 (2012) (in Japanese).

[13] M. Kakumoto, J. Yoneda, K. Miyazaki, N. Tenma, A. Masui, K. Aoki, H. Karasawa and R. Itoi: Preliminary study on well integrity during gas production from methane hydrate sediments, *Proc. Int. Symp. Earth and Technol. 2011*, CD-ROM (2011).

[14] A. Masui, H. Haneda, Y. Ogata and K. Aoki: Effects of methane hydrate formation on shear strength of synthetic methane hydrate sediments, *Proc. 15th Int. Offshore and Polar Eng. Conf.*, 364-369 (2005).

[15] A. Masui, K. Miyazaki, H. Haneda, Y. Ogata, and K. Aoki: Mechanical characteristics of natural and artificial gas hydrate bearing sediments, *Proc. 6th Int. Conf. on Gas Hydrates*, CD-ROM, (2008).

[16] K. Miyazaki, A. Masui, K. Aoki, Y. Sakamoto, T. Yamaguchi and S. Okubo: Strain-rate dependence of triaxial compressive strength of artificial methane-hydrate-bearing sediment, *Int. J Offshore and Polar Eng.*, 20, 256-264 (2010).

[17] K. Miyazaki, A. Masui, Y. Sakamoto, K. Aoki, N. Tenma and T. Yamaguchi: Triaxial compressive properties of artificial methane-hydrate-bearing sediment, *J. Geophys. Res.*, 116 (B6), 102 (2011).

[18] K. Miyazaki, Y. Endo, N. Tenma and T. Yamaguchi: A nonlinear viscoelastic constitutive equation for artificial methane hydrate-bearing sand under triaxial compression, *Proc. 8th Int. Conf. on Gas Hydrates*, CD-ROM, (2014).

[19] J. Yoneda, A. Masui, N. Tenma and J. Nagao: Triaxial testing system for pressure core analysis using image processing technique, *Rev. Sci. Instrum.*, 84, 114503 (2013).

[20] N. Tenma, K. Miyazaki, J. Yoneda, M. Kakumoto, K. Aoki, J. Mori, A Takiguchi and K. Hou: Sensitivity analysis for well integrity during gas production from methane hydrate sediments, *Proc. 3th Comprehensive Symposium on Methane Hydrate* (CSMH-3 2011), 55-56 (2011) (in Japanese).

[21] M. Kakumoto, J. Yoneda, K. Miyazaki, N.Tenma, K. Aoki and R. Itoi: Basic study on the frictional strength between the casing and cement in a methane hydrate production well, *Journal of MMIJ*, 129 (4), 116-123 (2013) (in Japanese).

[22] J. Yoneda, M. Kakumoto, K. Miyazaki, J. Katagiri, N. Tenma and K. Aoki: Effect of surface roughness on frictional strength of casing in the sand under high confining pressures –Basic studies of well stability for methane hydrate development (Part 2)–, *Journal of MMIJ*, 129 (6), 278-283 (2013) (in Japanese).

[23] J. Katagiri, J. Yoneda and N. Tenma: DEM simulation for evaluating the contact behavior between soil with solid, *Proc. 4th Comprehensive Symposium on Methane Hydrate* (CSMH-4 2012), 207-208 (2012) (in Japanese).

[24] E. Ogisako, S. Nishio and A. Denda: Case study on ground deformation in methane hydrate production, *Proc. 4th Comprehensive Symposium on Methane Hydrate* (CSMH-4 2012), 136-140 (2012) (in Japanese).

[25] N. Yokoyama, M. Hyodo, Y. Nakata, N. Yoshimoto and A. Kato: Triaxial shear characteristics of methane hydrate bearing sand simulated sediments of deep seabed in Nankai Trough, *Proc. 4th Comprehensive Symposium on Methane Hydrate* (CSMH-4 2012), 145-149 (2012) (in Japanese).

[26] Y. Konno, Y. Jin and J. Nagao: Study on enhanced methane hydrate recovery by using high pressure giant unit for methane hydrate analyses (HiGUMA), *Proc. 5th Comprehensive Symposium on Methane Hydrate* (CSMH-5 2013), 54-55 (2013) (in Japanese).

Author

Norio TENMA

Joined the Agency of Industrial Science and Technology's National Institute for Resources and Environment in 1990. Specialized in numerical modeling and evaluation of heat extraction characteristics of geothermal reservoirs, and engaged in the development of numerical simulators. Transferred to AIST's Methane Hydrate Research Center in FY 2009 to engage in the development of a geo-mechanical simulator for MH development. Currently aims to develop the evaluation technologies for sedimentary characteristics.

Discussions with Reviewers

1 Overall comment

Comment (Hiroshi Tateishi, AIST Chubu; Yusaku Yano, AIST)

This paper gives an overview of the developmental technology system for the "evaluation technology of sedimentary characteristics" within the R&D process at AIST's Methane Hydrate Research Center. The paper aptly summarizes the role of the Center in MH21, which is the administrative center of the national project for MH resource exploration, and the development of a geo-mechanical simulator which is the core technology, and evaluation of well integrity and wide-area deformation based on simulations. We consider this paper appropriate for *Synthesiology*.

2 The global positioning of MH development

Question (Yusaku Yano)

This paper discusses the technological development of MH exploration in Japan, which I believe is a challenge not faced anywhere else in the world in terms of new technology development. The readers may wish to know about the positioning of this technological development on the global stage. As background, in which regions or countries are MH resources distributed, and what is the level of technological development in other countries? What is the positioning of the Japanese technology concerning MH? Also, although MH21 has written a roadmap for development in Japan, are there any international research collaborations with the rest of the world? Is there a global roadmap?

Answer (Norio Tenma)

For the exploration of MH as a new resource, surveys are being carried out in the United States, Russia, Canada, China, and India, but their aims are chiefly to study the volumes of resource. Actual production technology is not being researched elsewhere in the world. Therefore, as concerns to global positioning, I have added the paragraph: "Similar research is in progress around the world, such as in the United States, Korea, China, and India. For example, Korea is engaging in a gas hydrate survey in the Tsushima Basin, and the US is surveying reserves, along with the earthquake exploration surveys, in the Gulf of Mexico, however, no offshore production tests have yet been conducted."

3 Relationship to existing resource exploration research

Question (Yusaku Yano)

On the point of using wells for production, MH is similar to conventional oil and natural gas, but I think you are adding a unique MH technological system to existing advanced technological systems for oil and natural gas production. Unlike the construction of a technological system from blank, when adding a new technological system onto a large existing technological system, I believe one thinks of doing it more efficiently and effectively. For the development of evaluation technologies for sedimentary characteristics, is there previous research on oil and natural gas that could be referenced, and is the research progressing effectively by improving on such earlier research? Are you actually engaging in such activity?

Answer (Norio Tenma)

We believe that sediment deformation, such as subsidence while applying the depressurization method, is an important challenge when investigating the potential for long-term, stable production. The topic of subsidence, for example, has been investigated in the field of water-soluble natural gas exploration. We assume that a similar phenomenon will occur in MH exploration. We engaged in R&D to gain an understanding of the mechanical characteristic of the MH bearing sediment and to evaluate using numerical simulation, using approaches similar to those employed for natural gas extraction. For example, when understanding the mechanical characteristics of MH, we assumed that MH had been newly added to the sediment layer, so the research was done in reference to the test methods used in soil mechanics. Specifically, since our MH samples are affected by pressure and temperature, we investigated a method of conducting mechanical tests while controlling these factors. As described in subchapter 3.1, "Development of the geo-mechanical simulator," the MH simulated sample was made by injecting gas into the frozen sand sample. There was no method for calculating the specific physical property values until this method had been established, so we regard it as a major accomplishment. However, we have conditions that are not encountered in conventional research, such as the target of exploration being a non-consolidated layer several hundred meters below the seabed floor, not to mention the near-explosive depressurization that takes place when using the depressurization method (about 7 MPa depressurization in the first offshore production test). We are now conducting our research taking these differences into full account.

4 Relationship with the offshore production test

Question (Hiroshi Tateishi)

In the offshore production test in March 2013, what preliminary contribution did this research make? Or was the simulator unable to make specific predictions since it was incomplete? As about one year has elapsed since the test, can you make any remarks about the results or their interpretation? I do understand that you may not be able to talk about the results for reasons of confidentiality, but considering the fact that you are two years into Phase 2 according to the schedule, I get the impression from this paper that it started with a bang but ended in a whimper.

Answer (Norio Tenma)

The analysis results were used as basic data for designing the wells for the first offshore production test and for setting the monitoring wells. However, a range of verifications are being carried out using the data from the first offshore production test, and as mentioned in this paper, we are still in the process of data verification for constructing and analyzing the numerical model and laboratory experiments. Therefore, the paper is simply a report on the current status.

5 Significance of development of the simulator

Comment (Hiroshi Tateishi)

While I understand that the development of a simulator is a key pillar of this research, the role and significance of the simulator is not clearly explained. Negatively speaking, I get the impression that the simulator development has become an end rather than a means. I think you should explain, in the early part of the paper, why the development of the simulator is necessary. Although it may be apparent to the people involved, it will not necessarily be clear to the general reader.

Answer (Norio Tenma)

To clarify the significance of the development of the geo-mechanical simulator, in chapter 1, "Introduction," I have added the sentence, "it is therefore necessary to develop evaluation technologies, such as a numerical simulator, that are able to predict sediment deformation behavior " after "To enable safe and long-term gas production from the MH layer…." In relation, I added the sentence, "However, the basic characteristics that must be handled in a numerical simulator … were not known at the start of the project, so we were unable to evaluate sediment deformation and consolidation."