RGC Ref.: N_PolyU518/16 NSFC Ref. : 51661165011
(please insert ref. above)

The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Experimental and Numerical Studies on Geomechanics of Methane Hydrate-bearing Sediments in South China Sea During Gas Production

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Dr LEUNG, Yat Fai	Dr LI, Dongliang
Post	Associate Professor	Associate Professor
Unit / Department / Institution	Department of Civil and Environmental Engineering, HK Polytechnic University	Guangzhou Institute of Energy Conversion
Contact Information	andy.yf.leung@polyu.edu.hk	ldl@ms.giec.ac.cn
Co-investigator(s) *(with title and institution)*	Dr UCHIDA, Shun Rensselaer Polytechnic Institute	

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 Jan 2017		
Project Completion date	31 Dec 2020		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31 Dec 2021		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To establish an experimental framework to characterize the petrophysical and geomechanical properties of methane hydrate-bearing sediments in South China Sea;

2. To develop an adaptive simulation framework for the prediction of gas production, and the geomechanical response of marine hydrate-bearing sediments during gas production operations. The framework continuously updates the model parameters to match in-situ response, so that subsequent predictions are refined throughout the production process;

3. To identify key material parameters through quantitative variance-based sensitivity analyses, which contributes to further enhancement of the experimental and simulation frameworks for methane hydrate-bearing sediments

5.2 Revised Objectives

Date of approval from the RGC: Not applicable

Reasons for the change: Not applicable

6. Research Outcome

Major findings and research outcome

A series of triaxial compression tests were carried out for hydrate-bearing sediments synthesized from soils in China and Europe, as reported in Deusner et al. (2019) and Guo et al. (2020), including different sample preparation procedures (gas saturated samples and water saturated samples), and degrees of hydrate saturation ranging from 22% to 45%. The effective confining pressures were also varied from 0.25 MPa to 1 MPa, to simulate the stress conditions for hydrate bearing soils at different depths below the seabed. The strain rates ranged from 0.006 to 0.624%/min in these tests to investigate the strain rate effects of hydrate bearing soils. It was found that the gas saturated hydrate bearing samples exhibit a significantly higher increase in strength compared to the water saturated samples, even with the same hydrate saturation. In addition, a notable "re-hardening" phenomenon was observed, where the shear stress increases again at higher strain levels after the post-peak softening behavior. A number of hypotheses for this phenomenon has been proposed and discussed in Deusner et al. (2019), including the micro-mechanical level changes in the hydrate formation/dissociation process during the shearing. A modified constitutive model has also been proposed to incorporate non-associated flow rule with a non-constant residual friction term, to match with the experimental results. .

From the analytical point of view, the extraction of methane gas from gas hydrate bearing sediments is a thermo-hydro-mechanical coupled process which involves complicated mechanisms and sophisticated numerical modelling techniques. In this study, an efficient sensitivity-driven optimization approach is formulated to identify key material properties at various stages during the process, to calibrate the associated parameters and predict future wellbore response including gas and water productions and the borehole displacements. The approach incorporates the metamodelling method using machine learning techniques (ANN), which is then extended for quantitative variance based sensitivity analysis and differential evolution for parameter calibration, while the sensitivity indices can also be utilized for probabilistic predictions of wellbore response in face of the uncertainty and heterogeneity of in situ material properties. In particular, the gas and water productions during hydrate dissociation are dominated by the intrinsic permeability (K) of the sediments and the hydrate dependent permeability (i.e. changes of K with hydrate saturations). Meanwhile, it is important to state that the borehole displacement during gas production operation is also heavily influenced by sediment permeability, illustrating the interacting nature of the mechanical-hydro processes. This approach is demonstrated through the 2013 Nankai offshore gas production test. Favorable matching of wellbore responses is achieved with adaptive calibration of one-third of the model parameters, as gas and water productions are dominated by the intrinsic and hydrate-dependent sediment permeability, whereas deformation is controlled by pre-yield plasticity and hydrate-dependent strength. The study also found that sensitivity of the wellbore response in hydrate reservoir could also depend on site-specific variability of these parameters. This means that while further experimental studies on these influential parameters will be beneficial to future gas production operations, field measurements on these in situ parameters will also lead to more indicative prediction range for the potential wellbore response.

Potential for further development of the research and the proposed course of action

This study establishes and publishes a dataset of experimental results, and a potential future development could involve study on the micro-mechanics of the behavior of hydrate-bearing sediments, based on these physical test data. This would entail discrete element modelling (DEM) of both hydrate-free specimens and samples with various hydrate saturations, to enhance the understanding on the particle level details of the response. In particular, the hydrate 'particles' are often considered to enhance the dilation and cementation of host specimens, and such effects, together with other features such as particle shapes of the host soil, can be explored with DEM.

Also, while the metamodeling techniques were developed to simulate geomechanical response and to study importance of various mechanical and flow parameters, it is possible to extend this approach to incorporate other influential factors associated with the site conditions (e.g., the pressure, temperature, hydrate saturation), operational variables (e.g., depressurization rate, production zone thickness), and also model parameters (e.g., kinetic coefficient) for hydrate formation and dissociation. Perhaps more importantly, hydrate reservoirs are often associated with significant heterogeneity, both in terms of material parameters and hydrate saturations (distributions). The influence of such heterogeneity on gas production and sediment deformations can be substantial, and can be investigated using various probabilistic methods such as random field simulations coupled with metamodels developed in this research.

7. The Layman's Summary

Methane hydrates are crystallines formed by intrusion of methane gas into water under high pressure and low temperature conditions, and have the potential to provide energy supplies for future generations. However, significant challenges are associated with commercial production of methane gas from hydrate-bearing sediments, partly due to the uncertainty in their response during the production operations. This study focuses on experimental and numerical investigations on the geomechanical behaviour of hydrate-bearing sediments from the South China Sea. In collaboration with the Guangzhou Institute of Energy Conversion, China, and Helmholtz Centre for Ocean Research, Germany, advanced triaxial tests were conducted on synthesized hydrate-bearing soils, to enhance the understanding on the effects of hydrate on the strength and stiffness of host sediments. The experimental data were used to modify existing theoretical framework on the simulation of these material behaviors. Making use of machine learning methods, efficient simulation techniques are developed to capture the coupled thermo-hydro-mechanical behavior in numerical analyses. These facilitate sensitivity analyses to identify the most influential parameters under the setting of production operations from hydrate reservoirs. The findings will be applicable to the hydrate exploration and gas production in China and around the world, helping to meet the ever-growing energy demands.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) ***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2019				C. Deusner*, S. Gupta, X.G. Xie, **Y. F. Leung**, **S. Uchida**, E. Kossel, and M. Haeckel	Strain-rate-dependent hardening-softening characteristics of gas hydrate-bearing sediment. *Geochemistry, Geophysics, Geosystems,* 20 (11), 4885-4905	No	Yes	Yes	Yes
2020				M. Zhou*, M. Shadabfar, H. Huang, **Y.F. Leung** and **S. Uchida**	Meta-modelling of coupled thermo-hydro-mechanical behaviour of hydrate reservoir. *Computers and Geotechnics*, 128, 103848	No	Yes	Yes	Yes
Expected 2021		✓		Y. Huo, **Y.F. Leung*** and C.Y. Kwok	Micro-mechanical perspective on the role of particle shape in shearing of sands	No	Yes	Yes	No
Expected 2021		✓		Z. Guo, Z. Wang, J.S. Lu; **D.L. Li***; D.Q. Liang; **Y. F. Leung** and X.P. Wu	Application of methane hydrate critical state (MHCS) soil model on multistage triaxial tests of methane hydrate-bearing sediment	No	Yes	Yes#	No
Expected 2022			✓	M. Zhou*, M. Shadabfar, H. Huang, **Y.F. Leung** and **S. Uchida**	Efficient back analysis of multiphysics processes of gas production from hydrate-bearing sediments through ANN-based metamodeling	No	No	Yes	No

the manuscript No. 4 is currently under review. Acknowledgement to RGC funding will be added in the revision stage.

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered

(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
June 2017, Denver, CO, USA	Sensitivity Analysis for thermo-hydro- mechanical response of hydrate bearing sediments during gas production operation	The 9th International Conference on Gas Hydrates (ICGH9)	2019	Yes	Yes	Yes

June 2020, Singapore (conference postponed to 2021)	Efficient back analysis of 2013 Eastern Nankai Trough gas production test based on machine learning technique	The 10th International Conference on Gas Hydrates (ICGH10)	No	Yes	Yes	Yes

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
HUO, Yingxu	PhD	4 September 2017	3 September 2021

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Established collaboration with Dr Christian Deusner of the Helmholtz Centre for Ocean Research (Germany), Prof. Masayuki Hyodo, Dr Hirotoshi Mori of Yamaguchi University (Japan), Dr Yang Wu of Guangzhou University (China), and Dr Mingliang Zhou of Tongji University (China). An international workshop on hydrate workshop was held in Yamaguchi University in November 2017 where the research output of this project was delivered in two presentations. A research seminar was also held in Guangzhou University in December 2018 with representatives from PolyU, Rensselaer Polytechnic Institute and Tongji University.

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	2 published; 2 under review; 1 under preparation	2	0	0	0