

RGC Ref.: N\_CUHK418/15

NSFC Ref. :

*(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**

Investigation of Characteristics and Mechanism of Earthquakes Associated with the Hutubi Gas Reservoir

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator <i>(with title)</i>	Professor WONG Teng Fong	Professor WANG Baoshan
Post	Professor & Director	Professor
Unit / Department / Institution	Earth System Science Programme, Faculty of Science, CUHK	Institute of Geophysics, China Earthquake Administration
Contact Information	tfwong@cuhk.edu.hk	wangbs@ceaigp.ac.cn
Co-investigator(s) <i>(with title and institution)</i>	Professor LIU Lin, CUHK Professor YANG Hongfeng, CUHK	N/A

**3. Project Duration**

	Original	Revised	Date of RGC/ Institution Approval <i>( must be quoted)</i>
Project Start date	1 Jan 2016	N/A	N/A
Project Completion date	31 Dec 2019	N/A	N/A
Duration <i>(in month)</i>	48	N/A	N/A
Deadline for Submission of Completion Report	31 Dec 2020	N/A	N/A

## **Part B: The Completion Report**

### **5. Project Objectives**

#### 5.1 Objectives as per original application

1. Systematic seismological investigation of earthquake activity near the Hutubi gas reservoir.
2. Geodetic analysis to measure the surface deformation associated with cyclic gas injections.
3. Laboratory measurement of the rock physics properties pertinent to induced seismicity.

4. Development of a 3D geomechanical model for the poromechanical response to gas injection and extraction, with realistic constraints from the seismological, geodetic and rock physics data.

## 5.2 Revised Objectives

Date of approval from the RGC: N/A

Reasons for the change: N/A

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- 1.
- 2.
3. ....

## 6. Research Outcome

Major findings and research outcome

(maximum 1 page; please make reference to Part C where necessary)

1. We have deployed a dense network for the proposed seismological observations. The high-quality data have allowed us to refine the velocity model and more accurately locate earthquake that developed in the vicinity of the Hutubi area using the double-difference method, particularly with reference to the faults that bound the reservoir units and the reservoir formation. Most importantly, we successfully determined the focal mechanism solutions of the two largest earthquakes (Mw 2.8 and 3.0) in August 2013 that are possibly related to an unmapped reverse fault gently dipping to the south. The key results were presented in a *JGR* paper by Zhou et al. (2019).
2. Our continuous GPS measurement and analysis of INSAR data have underscored the necessity to account for significant seasonal contributions to geodetic data from hydrological changes, before the geodetic data can be used to constrain the geomechanics. Core samples have been collected from outcrops and shallow boreholes for rock physics measurements. The petrophysical data were synthesized with available borehole data to derive a realistic hydromechanical framework for a fully coupled 2D poroelastic model. Unlike previous studies with a primarily seismological focus, ours is the first quantitative analysis of the geomechanics of seismicity associated with cyclic injection/extraction through developing a hydrogeologic framework, which systematically integrated geodetic, geophysical and geological data. We have been able to resolve horizontal ground extension and shortening on the order of cm in response to injection and extraction, which was not reported in other regions with induced seismicity. Our numerical simulations have revealed that the horizontal extension due to the reservoir dilation is larger than ground uplift, and in agreement with seismological observations of Zhou et al. (2019), the observed seismicity on faults without hydraulic connections to the gas repository was probably induced by the poroelastic effect of reservoir dilation. Our seminal study provides an interdisciplinary framework for detecting and characterizing the geomechanical behavior and seismic hazard in relation to cyclic fluid injection and extraction in a deep reservoir. This aspect of our project was presented by Jiang et al. (2020) in *EPSL*,
3. Techniques that have been developed in this project and their successfully implementation in Hutubi have motivated related studies on induced seismicity in Sichuan (fracking-induced, Yang et al., *SRL* 2020; Sheng et al., *JGR*, 2020), Xinfenjiang reservoir, Guangdong (He et al., *JGR* 2018) and Virginia (Meng et al., *JGR* 2018).

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

(maximum half a page)

Our study provides a prototype of an interdisciplinary project that systematically integrates geodetic, geophysical and geological data for detecting of induced seismicity and characterizing the geomechanical behavior of cyclic fluid injection and extraction in a deep reservoir, which would likely be applicable to underground repositories that are being established worldwide. Within China, there are a number of such facilities, where we intend to pursue similar investigations. There have also been a surge in seismicity related to fracking in shale formation, particularly in Sichuan. We have already initiated the investigation of these events, leveraging the seismological techniques that have been

developed in the current project. This line of research will be pursued proactively in the next few years.

## 7. The Layman's Summary

*(describe in layman's language the nature, significance and value of the research project, in no more than 200 words)*

There have been numerous reports of earthquakes induced by anthropogenic activities. In particular, a number of relatively large earthquakes in the past decade have been attributed to fluid injection in petroleum fields, which have motivated extensive seismological, hydrogeological and geomechanical investigations into the physical processes of induced seismicity. In comparison, there has been a paucity of scientific research on earthquakes induced by gas injection or production as well as cyclic gas injection-extraction, even though hundreds of storage facilities for natural gas have been established worldwide, including China. The Hutubi underground gas storage facility is the largest one in China, and is also a unique case with both earthquakes and ground displacements detected during multiple cycles of injection and extraction since 2013. Unlike previous studies with a primarily seismological focus, here we conducted quantitative analysis on the geomechanics of seismicity induced by the HUGS through developing a hydrogeologic framework, which systematically integrated geodetic, geophysical and geological data. Our project has provided a prototype scheme for detecting the earthquake hazard and characterizing the geomechanical behavior of cyclic fluid injection and extraction in a deep reservoir, which would be applicable to other geologic repositories in China and other countries.

## 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) <i>(bold the authors belonging to the project teams and denote the corresponding author with an asterisk*)</i>	Title and Journal/ Book <i>(with the volume, pages and other necessary publishing details specified)</i>	Submitted to RGC <i>(indicate the year ending of the relevant progress report)</i>	Attached to this report <i>(Yes or No)</i>	Acknowledged the support of this Joint Research Scheme <i>(Yes or No)</i>	Accessible from the institutional repository <i>(Yes or No)</i>
Year of publication	Year of Acceptance <i>(For paper accepted but not yet published)</i>	Under Review	Under Preparation <i>(optional)</i>						

2017				<b>Yang H F*</b> , <b>Liu Y J</b> , Wei M, Zhuang J C, Zhou S Y	Induced earthquakes in the development of unconventional energy resources. Science China Earth Sciences, 60, doi: 10.1007/s11430-017-9063-0	2017	Yes [8.0]	Yes	Yes
2018				He, L., X. Sun, <b>H.</b> <b>Yang</b> , J. Qin, Y. Shen, and X. Ye	Upper crustal structure and earthquake mechanism in the Xinfengjiang water reservoir, Guangdong, China, J. Geophys. Res., doi:10.1029/2017JB015404		Yes [8.1]	Yes	Yes
2018				Meng, X., <b>H.</b> <b>Yang</b> , and Z. Peng	Foreshocks, b value Map and Aftershock Triggering for the 2011 Mw 5.7 Virginia Earthquake, J. Geophys. Res., doi:10.1029/2017JB015136		Yes [8.2]	Yes	Yes
2019				<b>Zhou</b> , <b>P.</b> , <b>H.</b> <b>Yang*</b> , <b>B.</b> <b>Wang</b> , and J. Zhuang	Seismological investigations of induced earthquakes near the Hutubi underground gas storage facility, J. Geophys. Res., doi: 10.1029/2019J B017360		Yes [8.3]	Yes	Yes

2020				<b>Jiang, G.*, X. Qiao, X. Wang, R. Lu, L. Liu, H. Yang, Y. Su, L. Song, B. Wang, and T. F. Wong</b>	GPS observed horizontal ground extension at the Hutubi (China) underground gas storage facility and its application to geomechanical modeling for induced seismicity, Earth Plane. Sci. Lett., doi: 10.1016/j.epsl.2019.115943	Yes [8.4]	Yes	Yes
2020				<b>Yang, H*, P. Zhou, N. Fang, G. Zhu, W. Xu, J. Su, F. Meng, and R. Chu</b>	A shallow shock: the 25 February 2019 ML 4.9 earthquake in the Weiyuan shale gas field in Sichuan, China, Seismo. Res. Lett., doi:10.1785/0220200202,	Yes [8.5]	Yes	Yes
2020				<b>Sheng, M., R. Chu, S. Ni, Y. Wang, L. Jiang, and H. Yang</b>	Source parameters of three moderate size earthquakes in Weiyuan, China, and their relations to shale gas hydraulic fracturing, J. Geophys. Res., doi:10.1029/2020JB019932	Yes [8.6]	Yes	Yes

**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 ( <i>indicate the year ending of the relevant progress report</i> )	Attached to this report ( <i>Yes or No</i> )	Acknowledged the support of this Joint Research Scheme ( <i>Yes or No</i> )	Accessible from the institutional repository ( <i>Yes or No</i> )
6/2017/Hefei	Seismicity around the Hutubi underground gas storage, Xinjiang, China	SEG Workshop: Microseismic Technologies and Applications	2017	Yes [9.01]	No	No
11/2017/ Shenzhen	Detection and relocation of small earthquakes near Hutubi Gas Reservoir	Frontiers in Studies of Earthquakes and Faults	2017	Yes [9.02]	No	No
11/2017/ Shenzhen	Poroelastic analysis of cyclic gas injection/ extraction-induced seismicity with two-phase flow	Frontiers in Studies of Earthquakes and Faults	2017	Yes [9.03]	No	No
12/2017/ New Orleans	Seasonal and Daily Variations of Subsurface Velocity Revealed by the Air-gun Source in Binchuan, Yunnan, China	AGU annual meeting	2017	Yes [9.04]	No	No
12/2017/ New Orleans	Seismicity around the Hutubi underground gas storage, Xinjiang, China	AGU annual meeting	2017	Yes [9.05]	No	No
7/2019/Montreal	GPS-observed Horizontal Ground Expansion and its Application for Assessing Seismic Hazard Induced by Hutubi (Xinjiang, China) Natural Gas Reservoir	27 <sup>th</sup> General Assembly of the International Union of Geodesy and Geophysics		Yes [9.1]	No	No
12/2019/ San Francisco	Investigating the seismic migration and hazard at the Hutubi (China) UGS site based on a hydrogeologic framework	AGU annual meeting		Yes [9.2]	No	No

**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
Zhou, Pengcheng	Ph.D.	2016	August, 2020

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

**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]	7	7			