

RGC Ref.: N_CUHK430/16

NSFC Ref. : 41661164035

(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

Source characteristics of induced earthquakes associated with shale gas production in Weiyuan, Sichuan 四川威遠頁岩氣基地誘發地震震源性質研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator <i>(with title)</i>	Prof. Hongfeng Yang	Prof. Risheng Chu
Post	Associate professor Effective since 1 August, 2020	Professor
Unit / Department / Institution	Earth System Science Programme, Chinese University of Hong Kong 香港中文大學理學院地球系統科學課程	Institute of geodesy and geophysics, Chinese Academy of Science 中國科學院測量與地球物理研究所
Contact Information	hyang@cuhk.edu.hk	chur@asch.whigg.ac.cn
Co-investigator(s) <i>(with title and institution)</i>	Prof. Teng-fong Wong Earth System Science Programme, Chinese University of Hong Kong	N.A.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval <i>(must be quoted)</i>
Project Start date	01/01/2017	N.A.	N.A.
Project Completion date	31/12/2020	N.A.	N.A.
Duration <i>(in month)</i>	48	N.A.	N.A.
Deadline for Submission of	31/12/2021	N.A.	N.A.

Completion Report			
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Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Systematic investigation of seismicity near the shale gas field in Weiyuan, Sichuan.
2. Deriving focal mechanism, stress drop, and directivity of earthquakes induced by shale gas production.
3. Laboratory measurement of the rock physic properties pertinent to induced seismicity.
4. Development of a 3D geomechanical model for the poromechanical response to fluid injection, with realistic constraints from the seismological and rock physics data.

5.2 Revised Objectives

N.A.

Date of approval from the RGC: _____

Reasons for the change: _____

- 1.
- 2.
3.

6. Research Outcome

Major findings and research outcome

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

Major findings include deriving high-resolution earthquake catalog in the region using both permanent and temporary seismic network, with the state-of-the-art machine learning techniques (Wong et al., 2021; Zhou et al., 2021). The majority of earthquakes is

likely induced by pore pressure perturbation (Yang et al., 2021 SSA Abstract; Sheng et al., 2020), and some moderate-size earthquakes occurred on faults that were reactivated by fracking (Wang et al., 2020).

One intriguing finding in the Weiyuan shale gas field is the extremely shallow depth of damaging earthquakes. On 25 February 2019, an M_w 4.3 earthquake struck the region at 1:15 pm with a reported intensity of VI. Immediately after the quake, fracking activities nearby were temporally shut down, because the earthquake caused 2 fatalities and 12 injuries. This was the first deadly earthquake associated with fracking (Yang et al., 2020), and therefore our results had been reported in various media.

With constraints from InSAR and seismic data, we located the earthquake at 1 km below the surface, coinciding with the Molin fault that was illuminated from seismic reflection profiles (Wang et al., 2020). Such focal depth was extremely shallow for seismic events because a fault at depths shallower than 2 km is usually considered aseismic. Whether or not this earthquake was induced by fracking remains unclear (Liu et al., 2021 SSA Abstract), as the present mechanisms of induced earthquakes can not explain the spatial distance between the earthquake hypocenter and fracking activities. Why such an extremely shallow fault ruptured in earthquakes is also mysterious and demands further investigations (Yang and Yao, 2021), potentially leading to future studies of shallow earthquakes.

Potential for further development of the research and the proposed course of action
(*maximum half a page*)

As pointed above, why the shallow fault ruptured in a damaging earthquake remains unclear. Motivated by such research problems, investigations of high-resolution location of seismicity and fault structure are demanded. Indeed, the PI wrote another GRF proposal and got it funded in 2021, to continue the efforts to understand such an intriguing and critical question, as shallow earthquakes pose greater hazards.

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*)

In the past decade, significant efforts have been made in developing new energy resources to meet the globally growing demand. Accordingly, some processes such as shale gas development are well known to induce earthquakes. In this project, we investigated earthquakes in the Weiyuan shale gas field in the Sichuan Basin, China, through seismic methods and geomechanical modeling, to unravelling the mechanisms of earthquake occurrence. By utilizing the state-of-the-art machine learning earthquake detector, we detect and locate numerous earthquakes in the Weiyuan region. We find that most earthquakes in Weiyuan were associated with fracking activities and were possibly induced by pore pressure diffusion. However, damaging earthquakes occurred at very shallow depths, challenging our conventional view of seismogenic depth. Furthermore, the mechanisms leading to the M_4+ earthquakes in the region remain in debate and demands further efforts, which hold significant implications for seismic hazard assessment in the shale gas field in China.

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				Yang, H* , Y. Liu, M. Wei, J. Zhuang, and S. Zhou	Induced earthquakes in the development of unconventional energy resources. Science China Earth Sciences, 60(9), 1632–1644, doi: 10.1007/s11430-017-9063-0	2018-12-31	Yes	Yes	Yes

2019				<p>Zhou, P., Yang, H.*, Wang, B., and Zhuang., J.</p>	<p>Seismologic al investigatio ns of induced earthquakes near the Hutubi undergroun d gas storage facility. Journal of Geophysical Research: Solid Earth, 124, 8753–8770. https://doi.org/10.1029/2019JB017360</p>	2018-12-31	Yes	Yes	Yes
2020				<p>Jiang, G.*, X. Qiao, X. Wang, R. Lu, L. Liu, H. Yang, Y. Su, L. Song, B. Wang, and T. F. Wong</p>	<p>GPS observed horizontal ground extension at the Hutubi (China) undergroun d gas storage facility and its application to geomechani cal modeling for induced seismicity, Earth Plane. Sci. Lett., 530, 115943, doi: 10.1016/j.ep sl.2019.115 943</p>	No	Yes	Yes	Yes

2020				Sheng, M., R. Chu* , S. Ni, Y. Wang, L. Jiang, and H. Yang	Source parameters of three moderate-size earthquakes in Weiyuan, China, and their relations to shale gas hydraulic fracturing, J. Geophys. Res., 125(10), e2020JB019932, doi:10.1029/2020JB019932	No	Yes	Yes	Yes
2020				Wang, M. *, H. Yang , L. Fang, L. Han, D. Jia, D. Jiang, and B. Yan (2020),	Shallow faults reactivated by hydraulic fracturing: The 2019 Weiyuan earthquake sequences in Sichuan, China, Seismo. Res. Lett., 91(6), 3171-3181, doi:10.1785/0220200174	No	Yes	Yes	Yes

2020				<p>Yang, H.*, P. Zhou, N. Fang, G. Zhu, W. Xu, J. Su, F. Meng, and R. Chu</p>	<p>A shallow shock: the 25 February 2019 ML 4.9 earthquake in the Weiyuan shale gas field in Sichuan, China, Seismo. Res. Lett., 91(6), 3182-3194, doi:10.1785/0220200202</p>	No	Yes	Yes	Yes
2021				<p>Chen, H., X. He, H. Yang*, and J. Zhang</p>	<p>Fault-Plane Determination of the 4 January 2020 offshore Pearl River Delta earthquake and its implication for seismic hazard assessment, Seismo. Res. Lett., 92(3), 1913-1925, doi: 10.1785/0220200232</p>	No	Yes	Yes	Yes

2021				Jiang, G.* , L. Liu, A. J. Barbour, R. Lu, and H. Yang	Physics-based evaluation of the maximum magnitude of potential earthquakes induced by the Hutubi (China) underground gas storage, J. Geophys. Res., 126, e2020JB021379, doi:10.1029/2020JB021379	No	Yes	Yes	Yes
2021				Wong, Jeremy, W.C., J. Zi, H. Yang* , and J. Su	Spatial-temporal Evolution of Injection-Induced Earthquakes in the Weiyuan Area determined by Machine-Learning Phase Picker and Waveform Cross-correlation, Earth Planet. Phys., doi:10.26464/ep2021055	No	Yes	Yes	Yes

2021				Choo, J.*, A. Sohail, F. Fei, T. Wong	Shear fracture energies of stiff clays and shales, Acta Geotechnica, doi: 10.1007/s11440-021-01145-5	No	Yes	Yes	Yes
2021				Yang, H.* and S. Yao	Shallow destructive earthquakes, Earthquake Science, 34(1), doi:10.2938 2/eqs-2020- 0072	No	Yes	Yes	Yes
2021				Zhou, P., W. L. Ellsworth, H. Yang* , Y. J. Tan, G. C. Beroza, M. Sheng, and R. Chu	Machine Learning-Fa cilitated Earthquake and anthropogen ic source Detections near the Weiyuan Shale Gas Blocks, Sichuan, China, Earth Planet. Phys. doi: 10.26464/ep p2021053	No	Yes	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 (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)

12/2018/Washington DC, USA	Seismological investigations of potentially induced earthquakes near the Hutubi underground gas storage	2018 AGU Fall Meeting	2018-12-31	Yes	Yes	Yes
12/2019/San Francisco, CA, USA	Source parameters of the deadly February 2019 Rongxian-Weiyuan earthquakes rattling the shale gas field in Sichuan, China	2019 AGU Fall Meeting		Yes	Yes	Yes
05/2020/Online	Induced or triggered? The deadly February 2019 Rongxian-Weiyuan ML 4.9 earthquake in the shale gas field in Sichuan, China	2020 EGU General Assembly		Yes	Yes	Yes
04/2021/Online	Shallow Induced Seismicity in Sichuan, China: A Coupled Flow–Geomechanics Modeling Analysis	2021 SSA Annual Meeting		Yes	Yes	Yes

04/2021/Online	Mechanisms Inducing Earthquakes in the Weiyuan Shale Gas Field, Sichuan, China, Inferred from Dense Array Recordings	2021 SSA Annual Meeting		Yes	Yes	Yes
04/2021/Online	Spatial-Temporal Evolution Pattern of Earthquakes Illuminated by Machine Learning Methods and Waveform Correlation in Weiyuan Shale Gas Field, Sichuan China	2021 SSA Annual Meeting		Yes	No	Yes
08/2021/Online	Hydraulic Fracturing Induced Earthquakes in the Shale Gas Field, Sichuan A Case Study of Event Cluster in Shuangshi Town	IAGA-IASPEI 2021 (IAGA: The International Association of Geomagnetism and Aeronomy IASPEI: International Association of Seismology and Physics of the Earth's Interior)		Yes	Yes	Yes

10/2021/Online	Hydraulic Fracturing Induced Earthquakes in the Weiyuan-Rongxian Shale Gas Field, Sichuan: A Case Study of Event Cluster in the Shuangshi Town	ARMS11 (The 11 th Asian Rock Mechanics Symposium)		Yes	Yes	Yes
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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
Pengcheng Zhou	PhD	1/8/2016	16/8/2021

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

The trained PhD student Pengcheng Zhou won the prize of ‘The Global Scholarship Programme for Research Excellence 2019-20’ and committed oversea exchange studies between November 2019 and May 2020, in collaboration with Professor William L. Ellsworth and Gregory C. Beroza at Department of Geophysics, Stanford University, US.

During the project, we initiated collaboration with Sichuan Earthquake Agency, China and University of Bochum, Germany, in addition to our original collaborators in Institute of Geophysics and Geodesy, CAS, China. Such collaborations greatly help our investigations on earthquakes in the Weiyuan area and advance our understanding of induced earthquakes.

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

NSFC/RGC 8 (Revised 01/18)

	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]	12	8	0	0	0