

RGC Ref.: M-HKUST603/13 SRFDP Ref. : 20130094140001 <i>(please insert ref. above)</i>

**The Research Grants Council of Hong Kong
SRFDP & RGC ERG Joint Research Scheme
Completion Report**

*(Please attach a copy of the completion report submitted to the Ministry of Education
by the Mainland researcher)*

Part A: The Project and Investigator(s)

1. Project Title

English title: A Fundamental Investigation of PCC Energy Pile and Load Transfer
Mechanism: Geotechnical Aspects

Chinese Title: PCC 能源樁技術開發及其熱、力學特性研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator <i>(with title)</i>	Charles Wang-wai Ng	Hanlong Liu
Post	Chair Professor and Associate Vice President	Professor and Dean of College of Civil and Transportation Engineering
Unit / Department / Institution	Department of Civil and Environmental Engineering/HKUST	College of Civil and Transportation Engineering/Hohai University
Co-investigator(s) <i>(with title and institutions)</i>	Dr Hong Yi, Visiting Scholar, Department of Civil and Environmental Engineering/HKUST	Dr Gang-qiang Kong/Hohai University
PhD student(s) (with period of involvement)	Name: Anthony Gunawan Institution: HKUST Period from Jan., 2014 to Aug., 2017 (graduated) Name: Qijie Ma Institution: HKUST Period from Sept., 2014 to date Name: Mu Qingyi Institution: HKUST Period from Sept., 2014 to	Name: Shen Jie Institution: Hohai University Period from Fall 2014 to date Name: Xu Huang Institution: Hohai University Period from Fall 2014 to Nov., 2017 (graduated) Name: Li Chunhong Institution: Hohai University Period from Fall 2014 to date

	Aug., 2017 (graduated) Name: Cheng Qing Institution: HKUST Period from Sept., 2014 to Aug., 2017 (graduated)	Name: Wang Chenglong Institution: Chongqing University Period from Fall 2014 to date Name: Wu Di Institution: Chongqing University Period from Fall 2015 to date Name: Peng Huaifeng Institution: Hohai University Period from Fall 2015 to date
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Note: The Hong Kong project team must involve at least one research postgraduate student pursuing a Doctor of Philosophy degree at the UGC-funded university (PhD student) at any time throughout the project period.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval (must be quoted)
Project Start date	1 Jan., 2014		
Project Completion date	31 Dec., 2016		
Duration (in month)	36		
Deadline for submission of Completion Report	31 Dec., 2017		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To investigate and understand the thermo-hydro-mechanical interactions and efficiency of energy piles in sand, silt and clay, particularly large-diameter PCC energy piles;
2. To study and analyse the influence of the degree of saturation of unsaturated soils on pile capacity and the load-transfer mechanism under different combinations of temperature heating and cooling cycles and stress history;
3. To provide high-quality and comprehensive centrifuge model test data for calibrating existing and newly developed constitutive models and numerical analyses;

4. To add the capability of capturing the thermally-induced plasticity and dilatancy of saturated and unsaturated soils to an existing state-dependent thermo-hydro-mechanical constitutive model;
5. To develop a new form of heat-exchanger piles based on PCC piles;
6. To verify and refine existing design methods for energy piles;
7. To promote collaborations and exchanges between two universities and train PhD students and junior researchers

5.2 Revised Objectives

Date of approval from the RGC: N/A

Reasons for the change: _____

6. Research Outcome

Major findings and research outcome

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

The major key findings from this project are as follows:

- Floating replacement/bored energy piles will experience ratcheting settlement during initial service stage, irrespectively whether the pile is installed in sand or pile. This is due to the volumetric contraction and shearing at the soil-pile interface, leading to the reduction of horizontal stress.
- This ratcheting pile settlement decreases with the number of thermal cycles and it should be designed properly to minimize the serviceability life of any structure.
- On the contrary, small ratcheting heave behaviour of driven/jacked in floating energy piles is expected. The observed heave can be attributed to the densification effect and particle crushing of soil when the pile was jacked in, reducing or even eliminating the thermal contraction of sand and hence decrease reduction of horizontal stress during thermal cycles. This heave should be accounted for in design.

Outcome

- All the key technical findings are included in the first Chinese Technical Specifications for Geothermal Piles (中华人民共和国行业标准-桩基地热能利用技术标准) in the Mainland.
- More than 10 journal papers have been published jointly (refer to Part C: Session 8 for details).
- Three special issues have been organized by the PI and co-PI and published in three international reputational journals (refer to Part C: Session 11 – other impacts for details)
- Four patents have been granted. (refer to Part C: Session 11 – other impacts for details)
- One M.Phil and three Ph.D students have been trained to graduation and one more Ph.D student is expected to graduate in August 2018.

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

The research findings from this project are essentially based on model tests on single piles. More full-scale single pile tests should be carried out to verify the current findings and refine design guidelines. Moreover, research should also be carried out on energy pile groups and energy piled rafts in future.

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)

To enhance the sustainability of the Earth, energy piles has been explored for space heating by taking advantage of the Earth's ability to store heat. This is because the Earth's temperature at about 10 metres below the ground surface is fairly constant (Brandl, 2006). It is reported by Patel & Bull (2011) that space heating required in buildings and offices consumes up to 25% of the total energy that the world produces annually. By means of energy pile technology, which is combination of ground source heat pump technology and purposely designed piled foundation, the utilization of energy piles in the UK has shown to reduce the energy requirement and the carbon dioxide emission from heating and cooling by 60% and 50%, respectively. However, the use of energy piles has one major drawback: the circulation of heat-exchange fluids subjects piles to temperature fluctuations, which in turn induce extra axial load and additional settlement. Our current understanding of the thermo-hydro-mechanical interactions and load transfer mechanisms of energy piles in various ground conditions is still far from satisfactory.

In this project, the performance of single floating energy piles in sand and clay has been investigated and understood. Moreover, effects of different pile construction methods (replacement versus displacement piles) on the performance of energy piles have been carried out. It is found that replacement/bored energy piles experiences ratcheting settlement during initial service stage, irrespectively whether the pile is installed in sand or pile. This ratcheting pile settlement decreases with the number of thermal cycles and it should be designed properly to minimize the serviceability life of any structure in future. On the contrary, small ratcheting heave behaviour of driven/jacked in floating energy piles is expected. All the key technical findings are included in the first Chinese Technical Specifications for Geothermal Piles (中华人民共和国行业标准-桩基地热能利用技术标准) in the Mainland. In addition, more than 10 journal papers have been published and four patents have been granted.

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>)						
2014				Ng, C.W.W. , Shi*, C., Gunawan, A. & Laloui, L.	Centrifuge modelling of energy piles subjected to heating and cooling cycles in clay. <i>Géotechnique Letters</i> , Vol. 4, 310-316.	2017	Yes	Yes, page 316	Yes
2015				Ng, C.W.W. , Shi, C*, Gunawan, A., Laloui, L. & Liu, H. L.	Centrifuge modelling of heating effects on energy pile performance in saturated sand. <i>Canadian Geotechnical Journal</i> , Vol. 52, No. 8, 1045-1057.	2015	No	Yes, page 1056	Yes
2015				Zhou*, C., Xu, J. & Ng, C.W.W.	Effects of temperature and suction on secant shear modulus of unsaturated soil. <i>Géotechnique Letters</i> . Vol. 5, 123-128.	2015	No	Yes, page 127	Yes
2015				Huang*, X., Kong, G.Q., Liu, H.L. & Ng, C.W.W.	Experimental research on thermomechanical characteristics of PCC energy pile under cyclic temperature field. <i>Rock and Soil Mechanics</i> . Vol. 36, No.3, 667-673	2015	No	Yes, page 667	No
2016				Wang*, C.L., Liu, H.L., Kong, G.Q., Ng, C.W.W. & Wu, D.	Model tests of energy pile with and without a vertical load. <i>Environmental Geotechnics</i> , ICE, Vol. 3, No. 4, 203-213.	2017	Yes Online: http://dx.doi.org/10.1680/jenge.15.00020 .	Yes, page 10	No
2016				Jie Shen*, C.F. Chiu b*, C.W.W. Ng, Guohui Lei, Jie Xu	A state-dependent critical state model for methane hydrate-bearing sand. <i>Computers and Geotechnics</i> Vol. 75, 1-11,	2015	Yes online: http://dx.doi.org/10.1016/j.compgeo.2016.01.013 .	Yes, page 10	Yes

2016				Zhou*, C. & Ng, C.W.W.	Simulating the cyclic behaviour of unsaturated soil at various temperatures using a bounding surface model. <i>Géotechnique</i> . Vol. 66, No.4, 344-350.	2017	Yes	Yes, page 348	Yes
2016				Ng, C. W. W., Gunawan*, A., Shi, C., Ma, Q.J. & Liu, H. L.	Centrifuge modelling of displacement and replacement energy piles constructed in saturated sand: a comparative study. <i>Géotechnique Letters</i> . Vol. 6, 34-38.	2017	Yes, http://dx.doi.org/10.1680/jgele.15.00119 .	Yes, page 38	Yes
2016				Ng, C. W.W., Wang, S.H. & Zhou, C.	Volume change behaviour of saturated sand under thermal cycles. <i>Géotechnique Letters</i> , Vol. 6, No. 2, 124–131.	2017	Yes	Yes, page 130	Yes
2017				Fei, K.*, H.L. Liu, G.Q, Kong & Ng, C.W.W.	Implementation of a thermo-bounding surface model in COMSOL. <i>Rock and Soil Mechanics</i> . Vol. 38, No. 6, 1819-1826.	2017	Yes	Yes, page 1819	No
2017				Chen, Y.H., Xu*, J., Li, H., Chen, L., Ng, C. W. W. & Liu, H.L.	Performance of a prestressed concrete pipe energy pile during heating and cooling. <i>Journal of Performance of Constructed Facilities</i> , ASCE. Vol. 31, No. 3, 1-7	2017	Yes, DOI: 10.1061/(ASCE)CF.1943-5509.0000982	Yes, page 6	Yes
2016				Liu, H. L., Wang, C. L., Kong*, G. Q., Ng, C. W. W. & Wu, D.	Thermal-mechanical characteristics of energy pile under different degree of compaction. <i>China Science</i> , Vol. 11, No. 13, 1511-1516.	2017	Yes	Yes, page 1511	No

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)
Nov./2015/Bru ssels, Belgium	Model Tests on Thermal-Mechanical Characteristics of PCC Energy Pile in Saturated Sand.	<i>Second EAGE Workshop on Geomechanics and Energy 2015</i>	2015	No	Yes	Yes
Aug. /2016/ Kiel, Germany	A novel cavity expansion-based analytical tool and its potential application for energy pile foundation	<i>Proceeding of the 1st International Conference on Energy Geotechnics 2016</i>	2016	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
Shi Chao	M. Phil	1/9/2012	30/1/2015 (submitted in last report)
Anthony, Gunawan	Ph. D	1/9/2012	8/2017
Qijie, Ma	Ph. D	1/9/2014	On going
Mu Qingyi	Ph. D	1/9/2014	8/2017
Cheng Qing	Ph. D	1/9/2014	8/2017

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

Patents

1. 刘汉龙, 丁选明, 孔纲强, 吴宏伟, 陈育民. 一种 PCC 能量桩及其制作方法, (专利号: ZL201210298385.5), 授权公告日 2014 年 11 月 19 日
2. 孔纲强, 彭怀风, 吴宏伟, 丁选明. 一种地源热泵灌注桩钢筋笼内埋管的施工方法, (专利号: ZL201310302155.6), 授权公告日 2015 年 3 月 11 日
3. 孔纲强, 黄旭, 丁选明, 刘汉龙, 彭怀风. 一种六边形预制能量桩及其制作方法, (专利号: ZL201310442139.7), 授权公告日 2015 年 8 月 19 日
4. 孔纲强, 黄旭, 丁选明, 刘汉龙, 彭怀风. 一种预制能量桩的施工方法, (专利号: ZL201310441978.7), 授权公告日 2015 年 9 月 23 日

Trend-setting international conference

Professors Ng and Liu have jointly organized the 1st International Conference on *Geo-Energy & Geo-Environment (GeGe2015)* scheduled to be held between 4th and 5th December 2015. This is the first of its kind in the world. It is organized by HKUST, EPFL, Hohai University and Chongqing University and Zhejiang University and supported by Technical Committees (TCs) of the International Society for Soil Mechanics and Geotechnical Engineering: TC215 Environmental

Geotechnics and TC308 Energy Geotechnics, the Hong Kong Geotechnical Society and the Geotechnical Division of Hong Kong Institution of Engineers.

Prof. James Mitchell (Virginia Tech, USA), Member of US National Academy of Engineering (NAE) and Member of US National Academy of Sciences (NAS) and Prof. Kerry Rowe (Queens University, Canada), Fellow of Royal Society (FRS) and Fellow of Royal Academy of Engineering (FREng) have accepted our invitation to deliver IAS Distinguished Lectures at the Conference. Eleven international well-recognized scholars have also agreed to deliver their keynotes. These speakers include Professor Yunmin Chen (Zhejiang University), Professor Malek Bouazza (Monash University), Professor Yufeng Gao (Hohai University), Professor Hanlong Liu (Chongqing University), Professor Laloui Lyesse (EPFL), Professor Charles W.W. Ng (HKUST), Professor Carlos Santamarina (King Abdullah University of Science and Technology), Professor Kenichi Soga (Cambridge University), Professor Lizhong Wang (Zhejiang University) and Professor Tony Liangtong Zhan (Zhejiang University), Suzanne Lacasse (Norwegian Geotechnical Institute), who is a US NAE.

A conference flyer and details of the conference are given in the conference website:
<http://gege2015.org/>.

Moreover, selected extended abstracts from this conference were invited to extend them to full papers for rigorous review to have published in the following three special issues in three journals:

- Ng, C.W.W., Wang, Li-zhong, Zhan, Liang-tong & Hong, Yi (2016). Special Issue on Geo-energy and Geo-environment (GeGe2015). *Journal of Zhejiang University-Science A (Applied Physics & Engineering)*. Vol. 17, No. 7, 497-596.
- Ng, C.W.W., Liu, H.L, Gao, Y. F. & Archer, A. (2017). Themed issue on selected papers from the first International Conference on Geo-energy and Geo-environment 2015 (GeGe2015). *Geomechanics for Energy and the Environment* 10, 1–51.
- Ng, C.W.W., Chen, Y.M., Liu, H.L & Gao, Y. F. (2017). Special issue on Geo-energy and Geo-environment (selected papers from the first International Conference on GeGe2015). *Canadian Geotechnical Journal*. No. 54, Vol.11, 1523-1622: v, <https://doi.org/10.1139/cgj-2017-0601>

In 2017, the 2nd International Conference on Geo-Energy & Geo-Environment (GeGe2017) was held in Zhejiang University between 6 and 7th July. The GeGe2017 was organised by one of co-I: Dr Hong Yi of this project. The PI – Professor Ng was invited to deliver a keynote lecture during the conference. The 3rd International Conference on Geo-Energy & Geo-Environment is agreed to be held in Ecole Polytechnique Federale de Lausanne (EPFL) in Switzerland.