Innovations in the centrifuge modelling of energy pile behaviour in unsaturated soil

Anthony K. Leung[1,2], D. Vitali[2], L. Ma[3] and R. Zhao[2]

[1] Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong SAR
[2] Division of Civil Engineering, University of Dundee, Dundee, U. K.
[3]School of Resource and Safety Engineering, Central South University, China

ABSTRACT

Installing a row of discretely-spaced energy piles at the mid-height of an unsaturated soil slope has been proposed as an innovative means to increase the slope stability and also to harvest solar and geothermal energy for road surface de-icing. Centrifuge modelling of the thermomechanical interaction between unsaturated soils and energy piles is challenging. This paper aims to share three new inventions to improve our capabilities of modelling unsaturated soil-energy structure interaction in a geotechnical centrifuge, namely (i) small-scale model reinforced concrete (RC), to capture the thermomechanical behaviour and nonlinear quasi-brittleness of RC energy piles in prototype; (ii) centrifuge-mounted heating system, to deliver/extract heat energy into/from a model structure during a centrifuge flight; and (iii) large-size direct-shear box apparatus, to test the shearing behaviour of unsaturated soils, with and without reinforcing elements, under realistic stress and suction regimes. The performance of these inventions on an unsaturated soil-energy pile system relevant to the engineering application above is discussed in this paper.

Keywords: Energy pile; unsaturated soil; soil-pile thermomechanical interaction; centrifuge modelling

1 INTRODUCTION

Infrastructure slopes make up a large proportion of transport network in urban cities. The slope stability is largely controlled by the amount of matric suction in unsaturated soils. Under the impact of climate change, more intense and frequent precipitation is anticipated in many parts of Asia including Hong Kong and Taiwan and parts of the temperate Europe such as U. K.

Installing a row of discretely-spaced piles at the mid-height of slopes has been a common method for slope stabilisation. An innovative proposal put forward by the authors is to modify the reinforced concrete (RC) piles to be energy RC piles for solar energy storage and geothermal energy extraction (Fig. 1). Solar heat may be intercepted and stored in heat-carrier fluid in the pipes buried in the pavement. The heat harvested can be pumped to the piles for heat storage. Pile heating may evaporate soil moisture, potentially increasing suction and hence soil strength. Geothermal energy may be extracted by the energy piles for road surface de-icing.

A research project was commissioned to study the performance of this system. Centrifuge modelling has been chosen as the principal research tool to reveal the fundamental mechanisms of the interaction between energy pile and unsaturated soil and also to determine the effectiveness of using energy RC pile to increase soil lateral resistance. This project has brought up interesting, yet challenging, research questions:

- How can thermomechanical properties of RC energy pile be correctly captured in a scaled physical model?

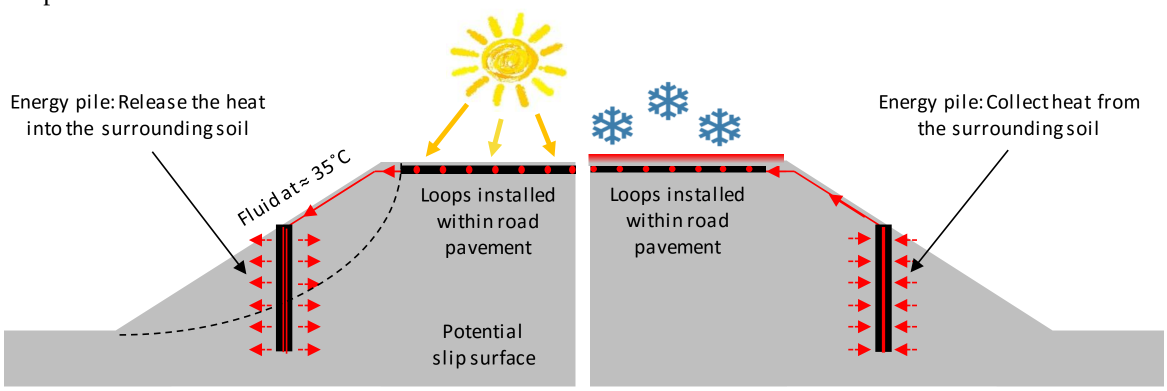

Fig. 1. A schematic diagram showing the key features of the newly-proposed engineering system.

- How can heat energy be effectively transferred in and out of an energy pile during a centrifuge flight?
- How would the lateral resistance of unsaturated soil be changed with pile heating and cooling?

This paper shares some recent, new technological and equipment developments to answer these specific research questions. The new inventions are:

- New small-scale model RC energy piles;
- Robust heating system that can be mounted onto a geotechnical centrifuge;
- New large-size direct-shear box for shearing a block of soil, with or without reinforcing system

2 NEW MODEL REINFORCED CONCRETE

In order to correctly capture the thermomechanical behaviour of RC energy piles in a physical model test, a new small-scale model concrete was developed. It is a mixture of β-form surgical plaster, water, silica sand and copper powder. The first three items are in the original mix of Knappett et al. (2011). The water/plastic and sand/plaster ratio are respectively fixed at 0.9:1 and 1:1, to resemble the mechanical properties of concrete in prototype (Knappett et al. 2011). Copper powder is newly-added in this study. This new addition aims to enhance the mix's thermal properties. Indeed, adding a more thermally conductive material (copper powder) into the mix increases almost linearly with the thermal conductivity of the model concrete (Fig. 2). 6 – 12% copper content (by volume) makes the model concrete to have a thermal conductivity close to that of the prototype. Further mechanical tests showed that the addition of copper power does not adversely affect the modulus of rupture (f_r) of the model concrete (Fig. 2).

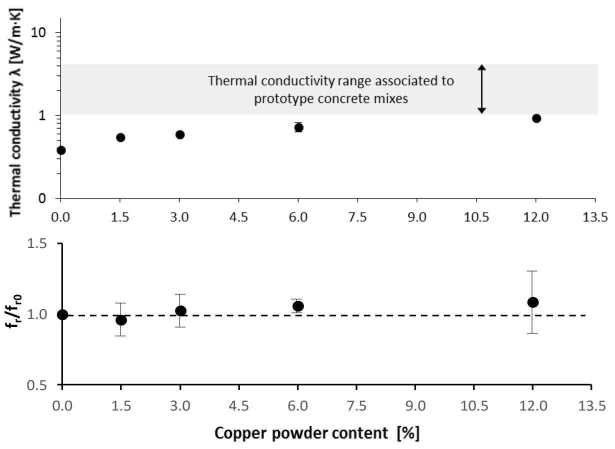

Fig. 2. Effects of copper powder content on thermal conductivity (n = 3) and normalised (by value with no addition of copper powder, f_{r0}) modulus of rupture (n = 6) of the new model RC.

3 DESIGN OF MODEL ENERGY PILES

3.1 Structural design

The new model concrete is used to create small-scale RC energy piles. As shown in Fig. 1, the main function of these energy piles is to stabilize soil slope, so these piles would be subject to lateral load predominantly. To achieve a design moment capacity of 230 kNm and following Eurocode 2 (BSI 2008), a doubly-reinforced 0.6 m x 0.6 m square pile with a length of 6 m and a reinforcement ratio of 2.1% is required. 24th scaled model piles were produced (Fig. 3). The reinforcements include longitudinal bars and stirrups which are both made of stainless steel. The stainless steel for making the bars and stirrups has a yield strength of 460 and 380 MPa, respectively. The steel has a thermal expansion coefficient of 18.5 με/°C.

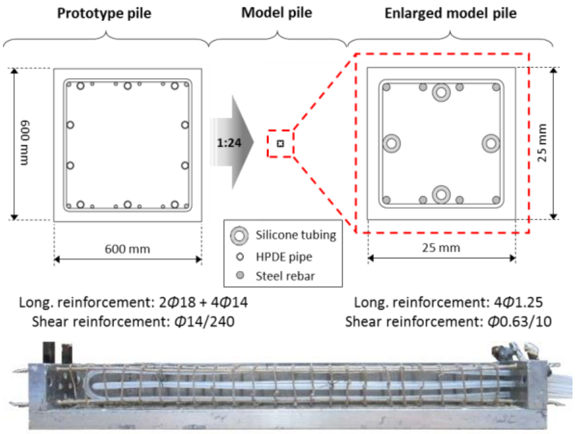

Fig. 3. Cross-section and reinforcement arrangements of energy piles before (top left) and after (top right) scaling. Picture at the bottom shows the internal arrangement of steels and silicon pipe.

To circulate heat-carrier fluid (water in this case) in and out of the model piles, a pair of silicone pipes with a model internal diameter of 1.5 mm was attached to the steel bars diagonal to each other, forming a double U-shape loop arrangement (see Fig. 3). As the model concrete hardens, the silicon pipes are connected to the heating system described in Section 4. The system can generate a turbulent flow regime within the embedded pipeline, maximizing the convective heat transfer mechanism from the pipes to the model concrete.

3.2 Thermomechanical properties

The linear coefficient of thermal expansion of the model RC energy piles was determined by subjecting them to four repeated heating-cooling cycles between 5 and 50 °C. The piles were allowed to expand or contract freely without mechanical constraint. Positive linear relationships were sought between the measured pile axial strain (by strain gauges) and pile surface temperature (by thermocouples). The gradient of the relationships, which is defined as the linear coefficient of thermal expansion, is ~9 με/°C, which is within the range for constraint RC pile in the field (6–10 με/°C; Bourne-Webb et al., 2009; Mimouni and Laloui, 2015).

Temperature effect on the flexural properties of the model pile was evaluated. Each pile was first heated or cooled to a constant temperature (at 5, 20 and 50 °C) and was then subjected to a four-point bending test. The temperature dependency of peak moment is a function of the content of copper powder (Fig. 4). Although it was tempted to add more copper powder into the mix to achieve a thermal conductivity closer to the prototype (Fig. 2), 12% was deemed too high to have reduced the moment capacity substantially (Fig. 4). 6% appears to be an optimal choice. In this case, the pile moment capacity was less affected by the pile temperature. The average moment at 6% is close to the theoretical value determined by the code, KSU_RC (Esmaely 2013).

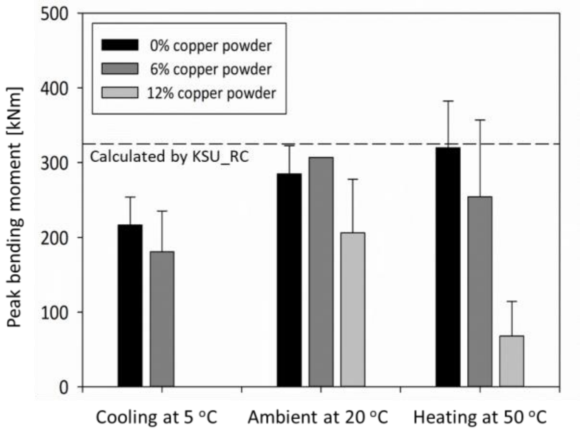

Fig. 4. Temperature effects on peak bending moment (n = 3), data presented in prototype scale.

4 NEW HEATING SYSTEM FOR CENTRIFUGE TESTING OF ENERGY STRUCTURES

A new heating system was developed to efficiently deliver/extract heat energy to/from model energy RC structures (e.g., piles in this study or others such as diaphragm wall) during centrifuge spinning. This is a crucial function as it allows for the study of not only the geotechnical performance of model structures, but also their energy performance (e.g., heat transfer efficiency), which is not commonly considered in previous studies.

The entire system is mounted on the centrifuge arm (Fig. 5), so no slip ring is required. This is a unique feature of the system, which is useful for small- to medium-size centrifuges that normally have limited slip rings. By using this system, the slip ring spared can be used to carry out other construction activities inflight, such as hydraulic jacking and earthquake simulation. In this system, the water reservoir stored in the aluminium tank can be heated by an electric heating rod. There is a temperature controller to maintain a target temperature by no deviating from ±1.5 ˚C. A magnetic pump is used to circulate hot water into the nylon pipes fixed along the centrifuge arm, and eventually into the silicon pipes and the model structures (Fig. 3) through a multi-port manifold (see Fig. 5). The pipes coming out from the model structure are connected to another manifold and finally to the top of the water tank through a nylon pipe.

Proof tests conducted up to 50-***g*** suggest that the system can produce a water flowrate up to 13.5 ml/s, which is sufficient to generate a turbulent flow regime within the water circulation pipe, hence maximising the favourable convective heat transfer mechanism between the silicon pipes to the model RC. More details about the working principle, calibration and performance of the system can be found in Vitali et al. (2018).

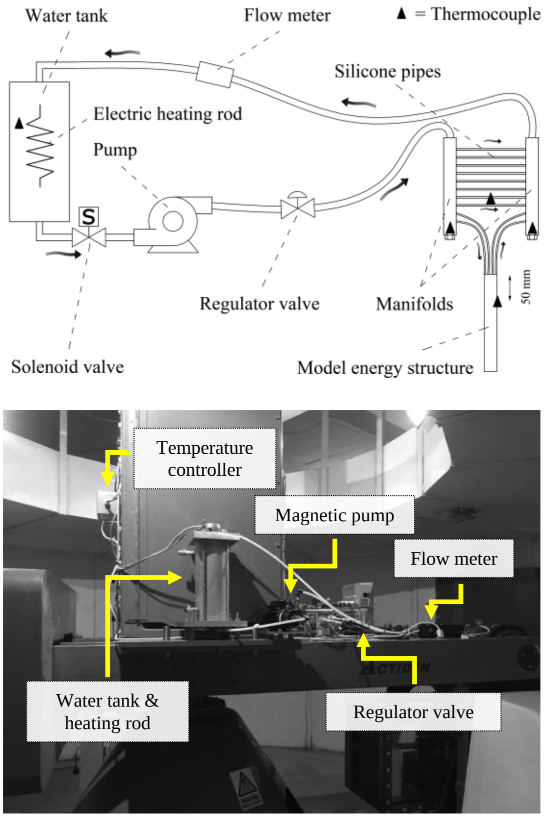

Fig. 5. Schematics (above) and overview (bottom) of the design of the centrifuge-mounted heating system (after Vitali et al. 2018).

5 NEW IN-FLIGHT LARGE-SCALE DIRECT-SHEAR BOX APPARATUS

The large-size (300 x 300 x 300 mm) direct-shear box apparatus shown in Fig. 6 is another new invention. For the first time, this apparatus can determine the soil shearing behaviour across different pre-defined depths of sliding plane in a geotechnical centrifuge. This apparatus is highly suitable for modelling translational slip and studying the underlying mechanisms of slope failure under realistic soil stress and suction regimes which would not otherwise be possible to recreate in 1-g condition. The apparatus can also evaluate the effectiveness of soil reinforcing systems such as piles, energy piles (this study), steel nails and plant roots. Specifically, combining the new shear box apparatus with the heating system in Section 4, any increase in the lateral resistance in the energy pile-reinforced soil due to pile heating/cooling can be determined, effectively evaluating the engineering performance of the proposed system in Fig. 1. The shear box can be equipped with multiple sensors such as thermocouples, soil moisture and suction probes for monitoring the soil hydrological and thermal responses before, during and after shearing.

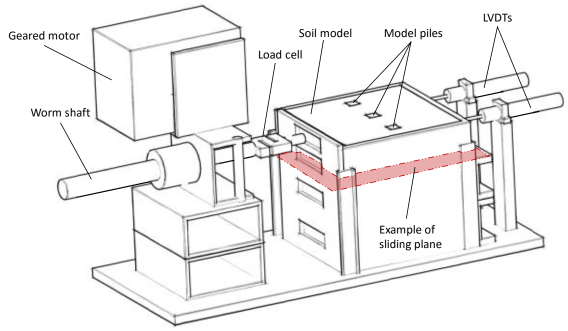

Fig. 6. The newly-developed large-scale direct shear box.

As an example of application, two centrifuge model tests using this new invention were carried out; one used a row of three model piles (spacing = four times pile diameter) to reinforce a block of unsaturated silt (Fig. 6), while the other test used energy piles. In both tests, shearing was applied at a sliding depth of 2.4 m (prototype) at 24-***g***. As can be seen in Fig. 7, pile heating changed the shape of mobilised pile bending moment profile significant, indicating a change in stress transfer mechanism in the soil-pile system. In-depth analysis requires data of load-displacement curves, of which the interpretation is underway. Nonetheless, after shearing, the energy RC pile located in the middle of the row showed significant plastic deformation, which occur mainly at the positions where maximum and minimum bending moment took place. This highlighted the success of using the new model RC to realistically mimic the nonlinear quasi-brittle nature of concrete, which is a key feature that is not achievable using elastic model piles (e.g., those made by aluminium).

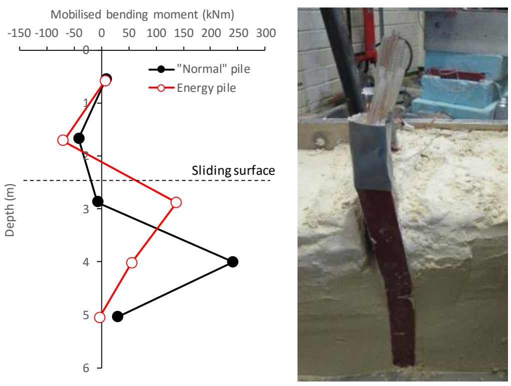

Fig. 7. (Left) Comparison of mobilised bending moment profile between "normal" pile and energy pile at a shear displacement of 0.24 m (prototype); (Right) Deformed shape of the model energy pile after shearing.

6 SUMMARY OF INNOVATIONS

Installing a row of energy piles at the mid-height of a slope has been proposed as an innovative system that can potentially enhance the engineering performance of an unsaturated slope. The use of energy piles offers engineers a new sustainable alternative to harvest clean and renewable solar and geothermal energy for (i) soil drying (hence potentially increasing soil strength and slope stability) and (ii) road surface de-icing. Physical modelling of this system using a geotechnical centrifuge is challenging. This paper shares some new inventions that aim to tackle these challenges and describes how they can be used to effectively investigate the complex thermomechanical soil-structure interaction within the centrifuge testing environment. The creations include:

(i) Small-scale reinforced concrete (RC), to realistically capture and reproduce the thermomechanical properties and the quasi-brittleness of concrete in prototype;

(ii) A robust centrifuge-mount heating system, with an aim to efficiently deliver/extract heat energy to/from any model energy structures during centrifuge test;

(iii) A large-scale direct shear box apparatus to study the soil lateral resistance, with and without reinforcing elements, under realistic stress and suction regimes

These three inventions, however, do not apply to the energy pile application exclusively. For example, an ongoing project led by the first author uses inventions (i) to produce model RC diaphragm wall and invention (ii) to "thermally activate" the model RC wall so that effects of cyclic heating/cooling cycle on wall structural responses and ground surface subsidence can be studied. The direct-shear box apparatus has also been recently used to study plant root reinforcement to soil for slope stabilisation and tree stability problems.

ACKNOWLEDGEMENTS

The authors thank the research funding provided by Energy Technology Partnership (ETP), Scottish Road Research Board (SRRB) from Transport Scotland and the EPSRC Doctoral Training Award.

REFERENCES

Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, C., and Payne, P. (2009). Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles. Géotechnique, 59(3), 237-248.

BSI (British Standards Institution). (2008). Eurocode 2: design of concrete structures: British standard. London, BSi.

Esmaely, A. (2013). KSU_RC: Moment Curvature, Force Deflection and Interaction Analysis of RC Members. Kansas State University, Civil Engineering Department.

Knappett, J. A., Reid, C., Kinmond S., and O'Reilly, K. (2011). Small-scale modeling of reinforced concrete structural elements for use in a geotechnical centrifuge. J. Struct. Eng., ASCE, 137,1263–1271.

Mimouni, T. & Laloui, L. (2015). Behaviour of a group of energy piles. Can. Geotech. J., 17, 1–17.

Vitali, D., Leung, A. K., Zhao, R., and Knappett, J. A. 2018. A new heating-cooling system for centrifuge testing of thermo-active geo-structures. 9th Int. Conf. on Phy. Model. in Geotechnics (ICPMG), London, U. K., 17th – 20th July, 2018.