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A new heating-cooling system for centrifuge testing of thermo-active geo-structures

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ABSTRACT: Centrifuge modelling has been considered as an effective means for investigating the energy and geotechnical performance of thermo-active geo-structures. A major challenge to correctly model (i) soil-structure heat transfer and (ii) thermo-mechanical behaviour of the geo-structure in a centrifuge is to design a system that could deliver sufficient heat energy (i.e. in terms of flowrate and temperature) under enhanced gravity conditions. This paper reports a new and robust heating/cooling system developed for these purposes and evaluates its performance. The proof heating tests performed up to 50-g suggest that when an appropriate pipe configuration is designed, the heating system is capable of producing 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 convective heat transfer mechanism. The heating system has been successfully applied to deliver a controllable amount of heat energy, simultaneously, to multiple thermo-active piles in a row for warming up the surrounding soil. With proper thermal insulation of the pipework of the system, temperature loss between the target value at the pipe inlet and the one registered at the entrance of the model structure could be less than 2°C. An idea for extending the system to lower the temperature below ambient is also presented.

1 INTRODUCTION

Thermo-active foundations are sustainable technology that do not only provide structural support to the superstructure but also exploit clean and renewable geothermal energy for satisfying the energy demand in the structure. Typically, this kind of foundation is made of reinforced concrete (RC), where high-density polyethylene (HPDE) pipe loops are embedded and attached along the steel reinforcement. The pipes are to circulate heat-carrier fluid so that the thermal energy could be exchanged between the supported structure and the soil surrounding the foundations. The cyclic thermal loading applied to the soil introduces thermal and mechanical stresses and strains to the RC foundation. Improved understanding of the complex soil-structure interaction associated with the combined thermo-mechanical loadings is required to inform engineering design.

Centrifuge modelling has been increasingly used to study the thermo-mechanical behaviour of thermo-active geo-structures such as a pile and its interaction with the surrounding soil under combined mechanical and thermal loadings. Compared to field experiments, testing small-scale models is relatively cheap and can be performed under much more controlled testing and boundary conditions. Hence, this approach can be used to isolate undesirable and uncontrolled field conditions (e.g. soil heterogeneity and groundwater flow), exclusively focusing on the complex soil-structure interaction involved. This is important for benchmarking numerical and analytical tools. The analysis performed by Rotta Loria et al. (2015) has shown that centrifuge model tests are capable of capturing fundamental aspects and provide highly consistent and comparable responses of thermo-active piles.

As far as the authors are aware, there are two active centrifuge facilities testing the geotechnical performance of thermo-active geo-structures, namely the University of Colorado Boulder (Stewart 2012, Stewart & McCartney 2014) and the Hong Kong University of Science and Technology (Ng et al. 2014, Shi et al. 2016). Both systems adopt a closed circuit system in which a circulating fluid transfers heat to/from the model energy geo-structure.

The system developed by Stewart (2012) uses a Julabo F25-ME heating/cooling water bath circulator that is set outside of the centrifuge chamber for controlling the temperature of ethylene glycol. The fluid is directed to a model structure through the centrifuge slip rings using a pump placed outside the centrifuge. The setup requires a pre-heating phase prior to centrifuge spinning so that all the components including the slip rings within which the fluid is circulating can reach a constant temperature for minimising heat losses. Thus, this system requires two slip rings for fluid circulation, which could limit inflight activities for small- to medium-size centrifuge facilities that have only a limited number of slip rings. Normally, inflight activities such as hydraulic jacking, earthquake simulation, application of rainfall would require at least one slip ring for operation.

The system developed in Hong Kong, on the contrary, avoids the use of multiple slip rings by introducing two independent components: one for the heating of the glycol-water solution and one for its cooling. The heating is achieved by using an electric heating element that is submerged in an aluminium tank filled with the circulating fluid. The cooling, on the other hand, is obtained through the Peltier effect to bring the fluid temperature below the ambient. The two components are arranged on the centrifuge together with a pump that allows the fluid to be delivered to the model foundations (Shi et al. 2016). The system requires a considerable amount of space to mount the two components onto a centrifuge and is therefore less suitable to be adopted by small- to medium-size beam centrifuges.

This paper details the development of a new heating/cooling system that can be mounted at the geotechnical beam centrifuge facility at the University of Dundee. Due to the limit of space, only the heating component of the system is discussed here. The working principle of the system is elaborated and its performance under different gravity levels is evaluated.

2 SYSTEM DESIGN

The design objective is to satisfy the following three conditions, namely (1) the need to flexibly both increase and decrease the internal temperature of model geo-structures through the circulation of heat-carrier fluid – to mimic the process occurring in the prototype; (2) the ability to operate under high gravity conditions; and (3) to avoid/minimise the use of dedicated centrifuge slip rings. Objective (1) is crucial for allowing the study of not only the geotechnical performance of the model, (i.e. thermo-mechanical responses of structure) but also energy performance (i.e. heat transfer efficiency) which has not been fully taken into account in previous centrifuge modelling studies.

Figure 1 shows the schematic and an overview of the design. The entire system is mounted on the centrifuge arm, so no slip ring is required. The system consists of an aluminium tank, a magnetic centrifugal pump, two nylon manifolds, a solenoid valve, a manual regulator valve and a series of sensors (i.e. k-type thermocouples and a flow meter) for monitoring the system efficiency. The tank can store up to 5.5 l of water. The water can be heated by a 1.0 kW electric heating element, whose temperature is controlled via a temperature controller and a submergible thermocouple. The temperature controller is used to maintain a desired temperature when it is deviated from the target value at the heating rod location by 1.5 ˚C. Once the target water temperature is reached, the pump can be switched on via an electromechanical relay to circulate the hot water into the nylon pipes fixed along the centrifuge arm.

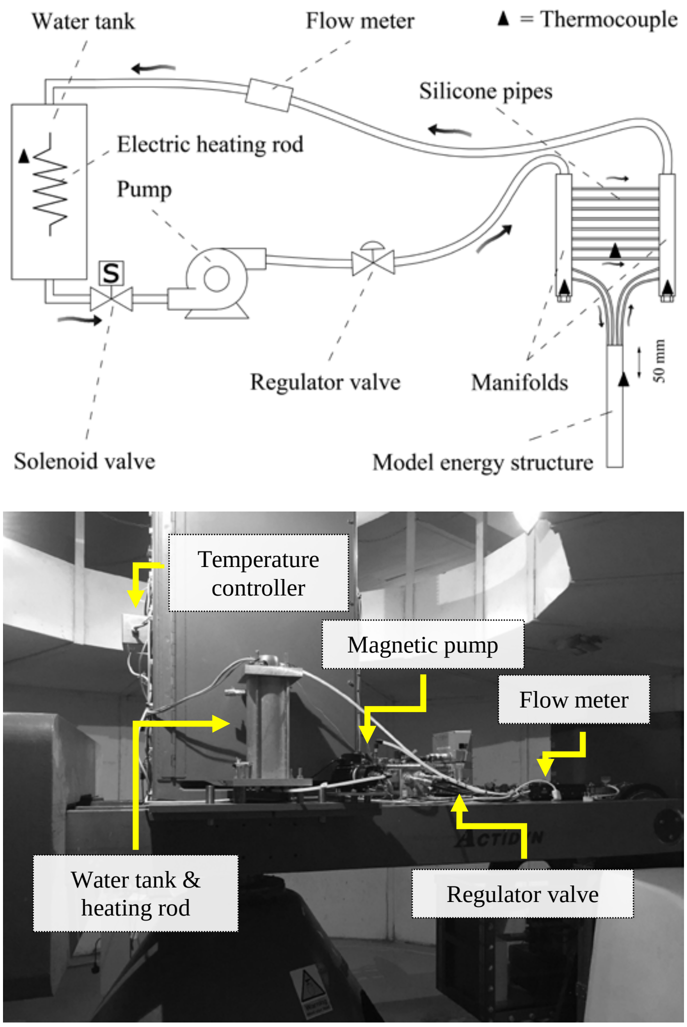

Figure 1. Schematic diagram (top) and overview (bottom) of the heating system mounted on the Dundee beam centrifuge.

A multi-port manifold is placed at the end of the nylon pipe for connecting with ten flexible silicone pipes which have an internal diameter of 1.5 mm each. These silicone pipes can be embedded in any model structure and are used to deliver the hot water to the structure. The pipes coming out from the model structure are then connected to a second identical manifold and finally to the top of the water tank through a nylon pipe. This forms a closed circuit.

A solenoid valve is placed between the water tank and the pump to isolate the water reservoir from the rest of the circuit in case any unexpected leakage happens along the circuit during a centrifuge test.

A regulator is installed behind the pump. The regulator, after calibration, can be used to adjust the water flowrate before the start of a centrifuge test. At the same time, a flow meter is placed behind the nylon manifolds both to verify whether the applied flowrate remains constant during the test and to check for any pipe leakage.

3 PROOF TESTING

Three centrifuge tests were conducted to evaluate the performance and functionality of the heating system under different g-levels ranging from 5- to 50-g. Test 1 aimed to evaluate any influence of g-level on the flowrate when circulating the hot water, while Tests 2 and 3 were to quantify the heat losses in the system.

In each test, a model thermo-active pile made of a new type of model concrete developed by Vitali et al. (2016) was connected to the manifolds. The model concrete has similar thermal properties (thermal conductivity and coefficient of thermal expansion) of concrete at prototype scale, so that the energy performance (i.e. temperature distribution and heat transfer efficiency) of the model pile could be evaluated. The model concrete scales the bending stiffness of the pile. The model reinforced concrete (RC) pile (Fig. 2) has longitudinal reinforcements from which hang two U-shaped silicone pipes for circulating the heat-carrier water, similar to what is similarly found in prototype RC thermo-active piles (e.g. Brandl 2006, Bourne-Webb et al. 2009). The model pile also has shear reinforcement links which are square in shape. Further details about the thermo-mechanical properties of the model concrete and the model pile made of this material may be found in Vitali et al. (2016) and Minto et al. (2016), respectively. Pile surface temperature was measured by a k-type thermocouple (see sensor location in Figure 1).

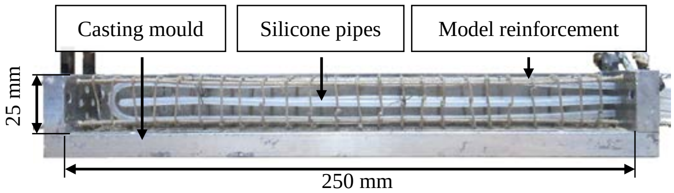

Figure 2. Detail of the reinforcement cage and of the silicone pipes embedded in the model thermo-active piles.

3.1 *Effects of g-level on water flowrate*

Prior to centrifuge spinning, the temperature controller was set to 50 ˚C and the heating element was activated. The regulator valve positioned after the magnetic pump was left fully open. The centrifuge was then spun up to 5-g, and then the pump was switched on to allow the hot water to circulate within the pipes. At steady state (when the flow meter measurement did not show any observable change for 4 min), the flowrate was recorded. Subsequently, the g-level was raised to 10-g and, again once a steady state was reached, the flowrate was recorded. This test procedure was repeated at 24-g, 30-g, 35-g, 40-g, 45-g and finally 50-g.

The water flowrates recorded under steady-state conditions at different g-levels are shown in Figure 3. There is an evident reduction of flowrate as the g-level increases, especially between 1-g and 10-g. The drop thereafter is less significant and seems to stabilise at a rate of ~0.9 l/min. The observed drop is attributed to the reduction of the efficiency of the magnetic centrifugal pump as the g-level increases. According to the number of pipes connected to the manifold and the pipe geometry, the observed range of flowrate represents a laminar flow regime. However, it is worth-noting that transitional and turbulent regimes, if desired, can also be achieved by reducing the number of pipes to four and two, respectively. The test results also suggests that the heating system is capable of circulating hot water with a reasonable flowrate for thermo-active piles with a wide range of pile size in prototype (from 125 x 125 mm at 5-g to 1.25 x 1.25 m at 50-g).

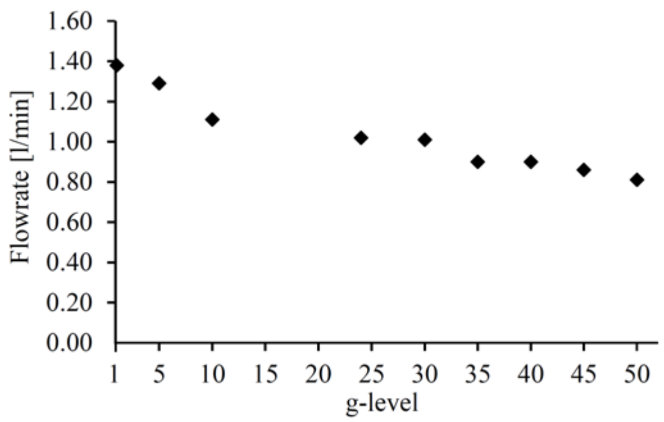

Figure 3. Steady-state flowrate (model scale) at different g-levels.

3.2 *Temperature distribution and heat efficiency*

Two tests, namely Test 2 and Test 3, were performed at 24-g to investigate the heat losses occurring along the system when nylon pipes were thermally insulated (Test 2) or not (Test 3). In these tests both the heating rod and the magnetic pump were switched on before spinning (i.e. at t = 0 min of Figure 4).

In both tests, the temperature was monitored at five different locations (Fig. 1): three of them measuring the temperature of the water circulating within the system (i.e. within the water tank and the two manifolds) and two recording the temperature of the external surface of both the silicone pipes and the model piles.

Figure 4 shows the temperature data obtained from the five different control points for Test 2. A progressive increase in temperature was recorded by all the thermocouples after the heating element was switched on and the pump was activated. Although the target temperature was kept constant at 50 ˚C at the heating rod location, the temperature of the water in the tank dropped slightly by 3 – 4 ˚C (i.e. down to 46 – 47 ˚C) as expected due to the heat exchange with the cooler air inside the centrifuge room during spinning (room temperature between 22 and 23.5 ˚C). Apparently, the temperature recorded in the water tank was oscillating by no more than 2.2 ˚C. This is an indication of the feedback system associated with the temperature controller, which tries to maintain the temperature at 50 ˚C by switching on and off the heating rod intermittently. The temperature drop at the pile surface at elapsed time of about 10 min is because of the reduction of pump efficiency when the g-level rose from 1 to 24 g (refer to Figure 3).

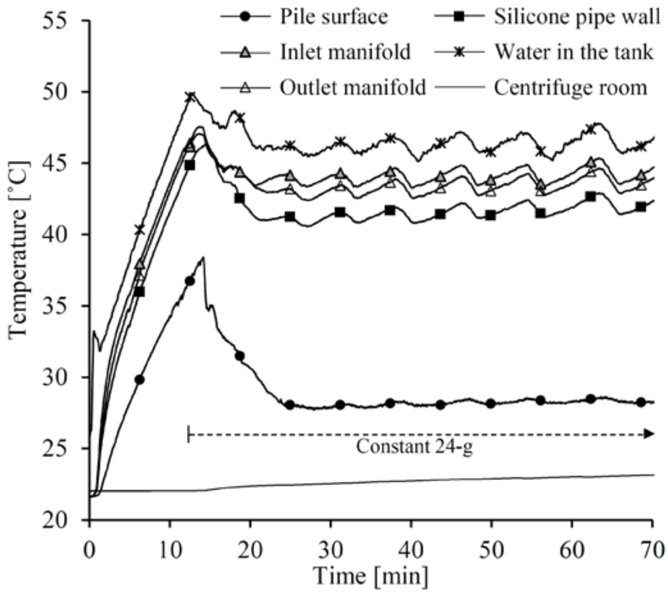

Figure 4. Temperature recorded during Test 2. Both the heating element and the pump were switched on at t=0 min. The spinning was started at t=2 min. Thermocouple positions are shown in Figure 1.

As the heat energy travels from the water tank to the inlet manifold at steady state, the mean temperature drop is less than 2.5 ˚C when thermal insulation is applied to nylon pipes. A further drop of temperature from 44.9 ˚C at the inlet manifold to 28 ˚C at the surface of the model piles (i.e. reduced by 16.9 ˚C) was recorded. This reduction was attributed both to the thermal resistance of the material of which the model pile is made (i.e. the internal silicone pipes and the model concrete) and to the heat lost due the wind generated by the centrifuge spinning. The thermal conductivity of the silicone pipes and model concrete are 0.12 and 0.73 W/(m·˚C), respectively (Vitali et al. 2016). For the given pipe thickness (0.75 mm) and cover thickness between the pipe and the pile surface (4 mm), it may be estimated by Fourier's law (i.e. assuming steady state heat conduction mechanism and neglecting superposition effects due to the double U-shape pipe configuration) that the pile surface temperature should be 30.9 ˚C. This means that no more than 17% of the heat loss was attributed to convective mechanisms occurring on the model surface due to the wind introduced by centrifuge spinning. In fact, during a centrifuge test, a wind cover may be applied to the centrifuge model box to minimise this kind of heat loss.

4 AN EXAMPLE OF SYSTEM APPLICATION

To further evaluate its performance for engineering applications, the heating system was connected to a row of three model thermo-active piles embedded in an unsaturated compacted soil. This centrifuge test (Test 4) aims to evaluate the temperature distribution in the piles and the surrounding soil through the circulation of hot water in the pile row.

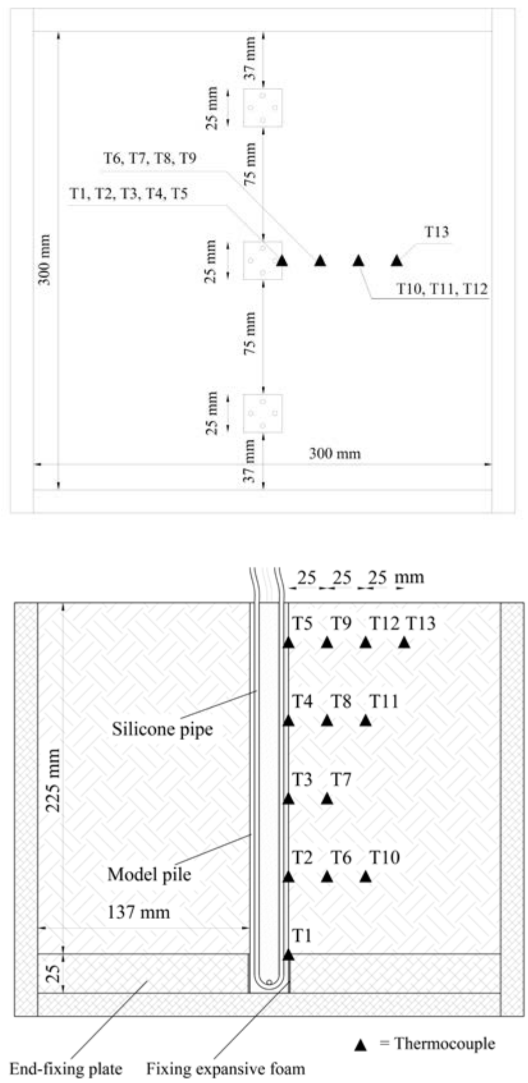

Figure 5. Plan view (top) and elevation view (bottom) of the centrifuge test setup in Test 4. Note that only results from T2, T4, T8 and T11 are presented in this paper.

A g-level of 24 was selected for this test, and the regulator valve was partially closed to control a steady-state flowrate of 2.22 ml/s in each one of the six silicone pipes connected to the manifolds. Details of the test setup are given in Figure 5.

The soil used was A50 silica flour, which is an artificial crushed soil with a quartz content higher than 99.5%. Some soil properties are summarised in Table 1.The soil was compacted to a target dry density of 1.58 g/cm^3 and an initial water content of 18% (by mass). During compaction, dummy aluminium piles were used to prevent any structural damage to the model RC pile. After soil compaction, the dummy piles were then replaced by the model RC ones.

Table 1. Properties of A50 silica flour.

Index Properties	
d_{10} [mm]	0.004
d_{50} [mm]	0.04
d_{90} [mm]	0.1
c' [kPa]	9
ϕ' (plane strain conditions) [°]	38˚
Thermal properties	
Coefficient of thermal expansion [10^{-6} °C^{-1}]	0.55
Thermal conductivity [W/(m °C)]	1.38
Van Genuchten (1980)'s hydraulic parameters	
K_s [mm/s]	$7.8 \cdot 10^{-4}$
θ_r [cm^3/cm^3]	0.0295
θ_r [cm^3/cm^3]	0.2844
α [cm^{-1}]	0.0022
n [-]	1.3313
l [-]	0.5

Note: K_s is saturate permeability; θ_r is residual water content (by volume); θ_s is saturated water content; α, n and l are fitting parameters that control the shape of the water retention curve

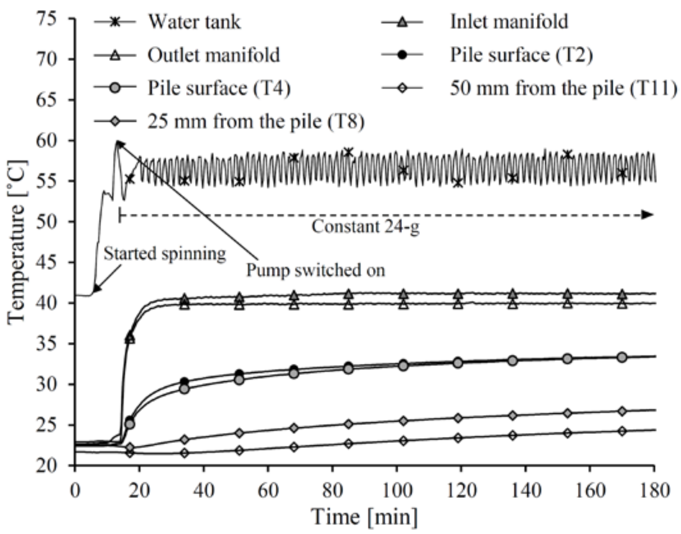

Figure 6. Temperatures recorded at different location during the 24-g test. Thermocouple positions are shown in Figure 5.

The target temperature set at the heating rod was 53 ˚C, while the temperature recorded at the inlet manifold is 40.6 ˚C (Fig. 6). Compared to Test 2, the greater heat loss in this test is because no thermal insulation was applied to the nylon pipes. It can be seen that the rate of increase of the pile surface temperature was relatively slower than in the manifolds. This is because of the equivalent thermal resistance of the model pile, which has a value of 1.64 ˚C/W. At steady state, the two thermocouples attached on the pile surface both showed 33.2 ˚C, meaning that there was 8 ˚C of temperature lost through the model material. This smaller reduction of temperature (compared to the 16.9 ˚C drop recorded in Test 2) is expected because the pile, in this case, was in contact with soil material, instead of air. Due to the pile embedment, convective heat loss at the pile surface was minimised.

The soil temperature recorded at horizontal distances of 25 and 50 mm from the pile surface shows that steady-state condition was not reached even after 165 minutes of spinning, corresponding to a prototype time interval of 66 days at 24-g.

5 ONGOING SYSTEM UPGRADE

The next phase of the system development is to incorporate a cooling component for applying and controlling the temperature of the heat-carrier fluid below ambient. The ultimate goal is to develop a holistic system that can flexibly apply cyclic thermal loadings (i.e. controlled heating/cooling cycles) to a model geo-structure during a centrifuge test

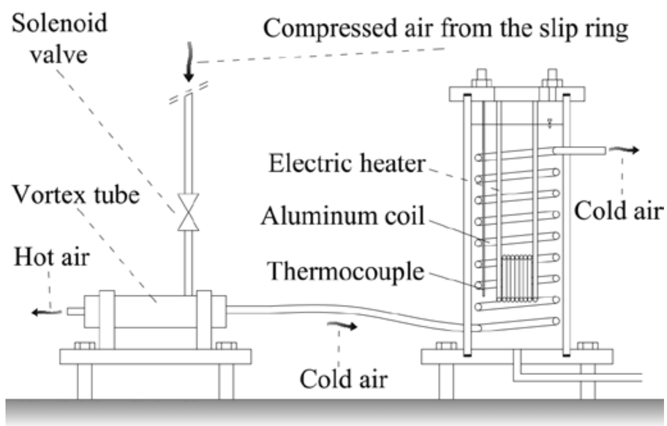

Figure 7. Schematic of the proposed cooling system.

Figure 7 shows the proposed modification. Cooling of the heat-carrier water can be achieved by using a Ranque-Hilsch vortex tube. Compressed air coming from a centrifuge slip ring will be injected into the tube. A vortex would be generated inside the tube to separate the compressed air into hot and cold streams and they will be ejected at the two ends of the tube. The stream temperature depends on the entering pressure and temperature of the compressed air. For example, compressed air with a pressure of 0.4 MPa and a temperature of 20 ˚C would produce a cold stream as low as 6 ˚C.

The cold stream will be then directed into an aluminium coil mounted inside the water tank. Hence the passage of the cold stream would cool the surrounding water (when the heating rod is switched off). Preliminary proof testing at 1-g shows that with proper thermal insulation of the water tank and the continuous circulation of the cold stream, the temperature of the heat-carrier water dropped to 7 ˚C.

In order to apply cyclic heating/cooling loads, the temperature controller will be replaced by a remote controlled one, which will switch the electric heating rod on and off following a prescribed thermal test path. When the heating rod is switched off, the relay-controlled solenoid valve placed between the slip ring and the vortex tube (Fig. 7) will be opened. Subsequently, the compressed air will be injected into the vortex tube and the cooling procedure starts.

The performance of the proposed modification of the system is currently under evaluation through a further series of 1-g and high-g centrifuge tests.

6 CONCLUSIONS

A new and robust heating system for centrifuge testing of thermo-active geo-structures was developed. The system is compact in size and does not require any slip rings because all its main components are placed on the side of the central centrifuge cabinet, leaving only the pipes and some sensors running along the centrifuge arm.

The performance of the heating system was evaluated at various g-levels between 1-g and 50-g using the University of Dundee beam centrifuge. The flowrate of the heat-carrier water circulating into, and from, a small-scale model thermo-active pile was g-level dependent. The steady-state flowrate reduces from 1.38 to 0.81 l/min as g-level increased from 1-g to 50-g. Nonetheless, the system is capable of reproducing any water flow regime in the 1.5 mm silicone pipes by controlling the number of pipes connected to the manifolds, in order to achieve any desirable condition that could maximise the heat transfer between the different elements of a centrifuge model (model structures and surrounding soil).

With a proper thermal insulation of the pipework of the system, the temperature drop between the target value (in the inlet manifold) and the one registered at the entrance of the model structure is less than 2 ˚C (i.e. equivalent to 5% when the target temperature in a model structure is set at 40 ˚C). As the heat energy diffuses through the model structure, heat losses into the air through the convection mechanism due to the centrifuge spinning are minimal. This kind of heat lost could be further eliminated by applying an aerodynamic cover on the model box.

The robust heating system has been successfully applied to deliver controllable amount of heat energy to a row of thermo-active piles for heating up the surrounding soil. Ongoing work is underway to further expand the capability of the system for controlling the temperature of the heat-carrier water below the ambient, hence applying heating/cooling cycles.

7 ACKNOWLEDGMENTS

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