Geotechnical challenges in providing ground source cooling through pile foundations

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ABSTRACT. Pile foundation heat exchangers (PFHX) have the potential to significantly reduce the carbon emissions associated with air conditioning for commercial buildings. UK adoption of PFHX, although increasing, is still very low due to the uncertainty about their performance and structural integrity. This study aims to highlight the areas of research that have been conducted and the scope of the work carried out in this area alongside further research on the effect of cyclic temperature variation in clays. This research is recommended in order to produce a framework for responses to a pile foundation operating as a heat exchanger. This is one of the areas identified for further investigation to improve the confidence and reliability of PFHX in order to become a more broadly adopted technology.

KEYWORDS. Clay; Cyclic temperature; Heating; Cooling; Microstructure.

INTRODUCTION

Pile foundation heat exchangers (PFHX) have the potential to significantly reduce the carbon emissions produced by air conditioning in large commercial and public buildings. By 2020 it is expected that around 40% of commercial floor spaces will be air-conditioned. This is at a time when the Energy Performance of Buildings Directive (EPBD) is influencing the UK building regulations, providing challenging targets for the conservation of fuel and power [1]. A change in refrigerant legislation is also forcing companies to look towards alternative cooling strategies [2].

PFHX require a heat exchanger loop to be incorporated into the pile foundation, however installation follows that of traditional piles; driven and cast in-situ piles can both be utilised as heat exchangers. The heat exchanger loop works in combination with a heat pump to allow for heat energy in the building to be transferred into a refrigerant that circulates within the heat exchanger loops and into the ground surrounding the foundation [3]. This poses the potential for a long-term build up in the ground temperature surrounding a PFHX, especially if many are used across several congested city sites. Given the UK climate, stakeholders predict that in the future 60% of a year there will be a demand for cooling which would cause thermal cycling of the ground around a PFHX [2]. Such thermal cyclic effects have the potential to be significantly damaging to long-term foundation performance in certain soil types.

This paper summarises the main areas that pile foundation heat exchangers have been studied and the areas of further research required in order for industry to further invest in this technology as a valid solution to low emission air conditioning in commercial buildings.

FIELD STUDIES

Across Europe there have been a limited number of field studies carried out to identify the potential of pile foundation heat exchangers and the problems that may arise. A successful PFHX would be one which performers within the tolerances of a standard pile foundation whilst allowing for efficient heat exchange into the surrounding ground. Across the case studies, information and varying operational use has been omitted, such as ground properties, meaning accurate interpretation of outcomes cannot be reliably determined. The most extensive field studies have been carried out at Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland and Lambeth College, London, UK.

The study at EPFL [4] considered a 4 storey building, 30 m by 100 m founded on 97 PFHX. The test pile had a given diameter of 0.88 m and length of 25.8 m. Installed in predominately moraine, the pile was subject a 15 °C temperature increases following an initial temperature increase of 21 °C with a maximum structural load of 1300 kN. Thermal loading and structural loading of the pile, as the buildings construction progressed, were not carried out simultaneously. An alternating sequence was carried out upon completion of a structural section. The testing at EPFL aimed to provide validation for finite element modelling to simulate the behaviour of PFHX during operation. During the test period of 28 days, a net displacement of 1 mm at the pile head was witnessed, however a maximum displacement of 4 mm was observed in the middle of the test period. Conclusions of the testing reported thermo-elastic strains within the pile, with their intensity dependant on the type of surrounding soil. Due to the difference in directional movement, uplift for thermal loading and settlement for static loading, the friction resistance of the pile was deemed not to be impacted, however relief of side friction mobilisation was observed during heating. As the induced thermal strains are limited, it is thought by Laloui et al. [4] that there is no affect on the pore water pressure or the effective stress. The EPFL study provides evidence that temperature load cycles contribute to vertical movement of a pile foundation, however Laloui et al. does not provide evidence for the nature of the movements; this could be due to the expansion and contraction of the pile itself or the surrounding ground, or a combination of both.

The study at Lambeth College [5] the authors aimed to address the thermo-dynamic behaviour of an energy pile during heating and cooling cycles. Testing was carried out during the construction of a 5-storey building founded on 143 pile foundations, installed in London Clay, with a diameter of 0.6 m and lengths ranging between 19 m and 24 m. An average structural load of 1025 kN was applied to the piles, with a heating load imposed on the piles ranging from -6 °C and 56 °C. Following a periods of pile cooling and heating, daily heating and cooling cycles were carried out. The net pile head displacement over the duration of testing was 3 mm, with a maximum displacement of 10 mm. Similarly to the EPFL field study; it is not possible to determine the nature of this displacement. The displacement could be attributed to the expansion and contraction of the concrete, the surrounding ground or a combination of both elements.

PILE DESIGN

Design guides produced by the Ground Source Heat Pump Association [6] for the installation of PHFX consider only the temperature effects of PFHX systems rather than the long-term cyclic temperature effects which would replicate actual PFHX operation. Bourne-Webb et al. [7] has produced a descriptive framework following on from the Lambeth College field study [5]. The framework developed analyses the strains that occur within the pile foundation during heating and cooling. The pile is considered as a free body, a perfectly restrained body and a PFHX with mechanical head load, during both heating and cooling. The framework produced by Bourne-Webb et al. [7] is comparable, to certain degree, with the observed field study results by the same author, however the results provided do not take into consideration variations in ground properties and the progressive responses to thermal cycles. Bourne-Webb et al. [7] consider the soil-structure interaction comparable to that of excavation heave or negative skin friction with the addition of the soil deformation resulting from the internal deformation of the pile with temperature variation. Bourne-Webb et al. [7] do not consider the deformation in the soil as a response to the thermal variation as part of their framework of pile behaviour. Loveridge & Powrie [3] have identified that during PFHX operations heat will be transferred to the soil, by means of conduction through the pile concrete, to surrounding the pile foundation. Experimental studies have identified that a significant response to thermal variation can be witnessed in soil behaviour; in addition to the interactions detailed by Bourne-Webb et al. [7], a soils response to change in temperature will be present and influence the piles behaviour.

EXPERIMENTAL STUDIES

Current literature presents very little information on the influence of cyclic temperature variation imposed on the pile to soil interface. In early studies, the response of clay to temperature was considered with regard to the shear strength [8] volume change and pore pressure variation [9]. A recent study by Abuel-Naga et al. [10] has considered the impact of temperature on a range of general engineering properties. These include permeability, compressibility and shear strength through a study on soft clay with low plasticity. Other studies have addressed individual engineering properties including the effect on overconsolidation ratio [11] and plasticity [12]. However, these studies have been carried out for individual clay types and discrete temperature increases. Results from these studies have yet to be unified into a single framework for pile design.

Campanella & Mitchell [9] identified that during heating, a change in sample height occurred. What is not known from the investigation is whether the change in height of the sample was attributed to a change in diameter of the sample i.e. barrelling or isotropic expansion. It is possible that radial expansion of the sample may occur due to the isotropic expansion of the sample during heating followed by anisotropic contraction of the sample during cooling, with axial contraction dominating.

Abuel-Naga et al. [10] and Cekerevac & Laloui [11] both concluded that the stress history of a sample influences the degree of thermal expansion or contraction produced through heating. Normally consolidated and lightly overconsolidated samples were found to contract, with heavily overconsolidated samples dilating upon heating. Although not evidenced, Campanella & Mitchell [9], Abuel-Naga et al. [10] and Cekerevac & Laloui [11] stipulate that the change in sample temperature produced an effect on fabric of the clay with interparticle forces and the viscous shear resistance of the absorbed water being affected. The understanding of these changes will significantly aid the future interpretation of thermal effects.

With regard to the effect of temperature on the stiffness and shear strength of a clay, Abuel-Naga et al. [10] identified that higher temperatures increased the shear strength and stiffness of Bangkok clay. However, evidence of this in current literature relating to other clay types has not been identified. Towhata et al. [12] conducted tests on kaolin and bentonite samples within a temperature controlled oedometer. Samples were incrementally heated whilst their void ratio was monitored. Testing showed that during heating a reduction in void ratio of 3% for kaolin and 12% for bentonite was observed. As testing was for heating only the effect of cyclic void ratio change during the cooling stages require further investigation.

In the current literature there is a consensus that the clay in which the PFHX is situated will function in an undrained condition during a change in temperature. The drainage state of the clay is dependent upon its permeability. Testing clays with varying plasticities over multiple cycles will build upon the work of Towhata et al. [12] whilst identifying thermal trends allowing for verification of previous studies such as Abuel-Naga et al. [10], Towhata et al. [12] and Cekerevac & Laloui [11] in order to produce a frame work for pile design incorporating temperature variations.

FUTURE RESEARCH

To further develop the PFHX industry, reliable yet broad guidance on the variation in strength and stiffness of clay following multiple cycles of temperature variation is required. As highlighted, one of the areas of weakness is an understanding of clays response to cyclic temperature variation and the impact this has on foundation design. Testing to address the long term effects of PFHX on the clay surrounding the soil-pile interface is to be carried out using a modified triaxial system influenced by the system developed by Laloui et al. [4]. The triaxial system simulates infield conditions by allowing control of both stress and temperature simultaneously within the cell. The system developed at the University of Sheffield (Fig. 1) incorporates a copper-heating coil installed to allow for temperature of the water within the triaxial.

An expansion ring at the base of the cell was commissioned for the installation of thermocouples within the cell. These thermocouples are used in the calibration of the test system and monitoring of the temperatures during testing. To regulate the temperature of the cell a bespoke heating system was manufactured. This included a regulated heated water bath and central heating pump with a maximum pressure of 6 bar and a maximum flow rate of 3.5m^3/h, in order to circulate water at a high enough pressure to enable efficient heating. Staged heating and cooling is carried out using a program developed in Labview. This operates as a thermostat, with the desired temperatures being input. In order to further identify the changes that occur within the sample during the thermal cycles, local linear variable differential transformer (LVDT) will be installed on the sample. The pressure and volumes within the cell, sample and loading ram will be controlled using GDS Instruments pressure transducers. These will allow for an automatic maintenance of pressures independent of volume change.

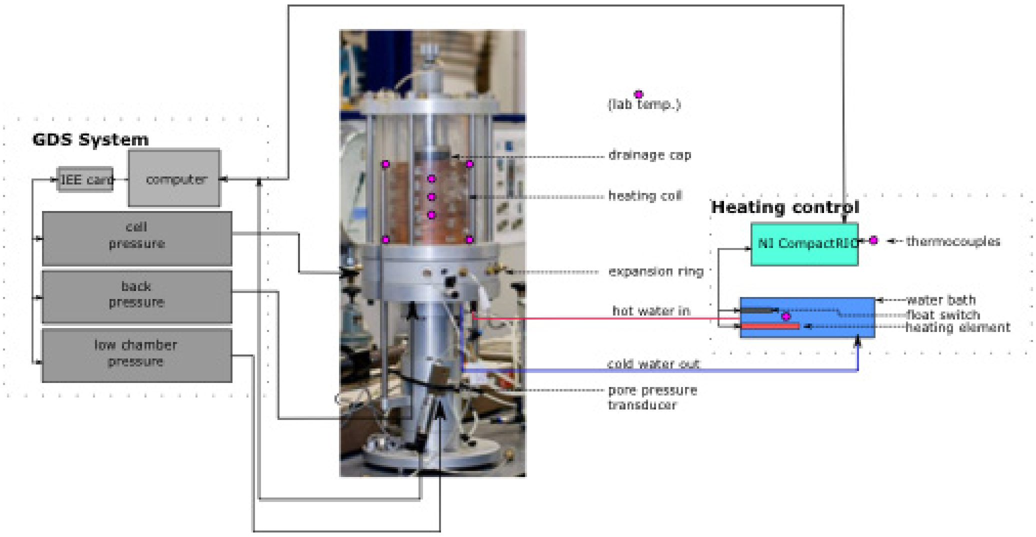


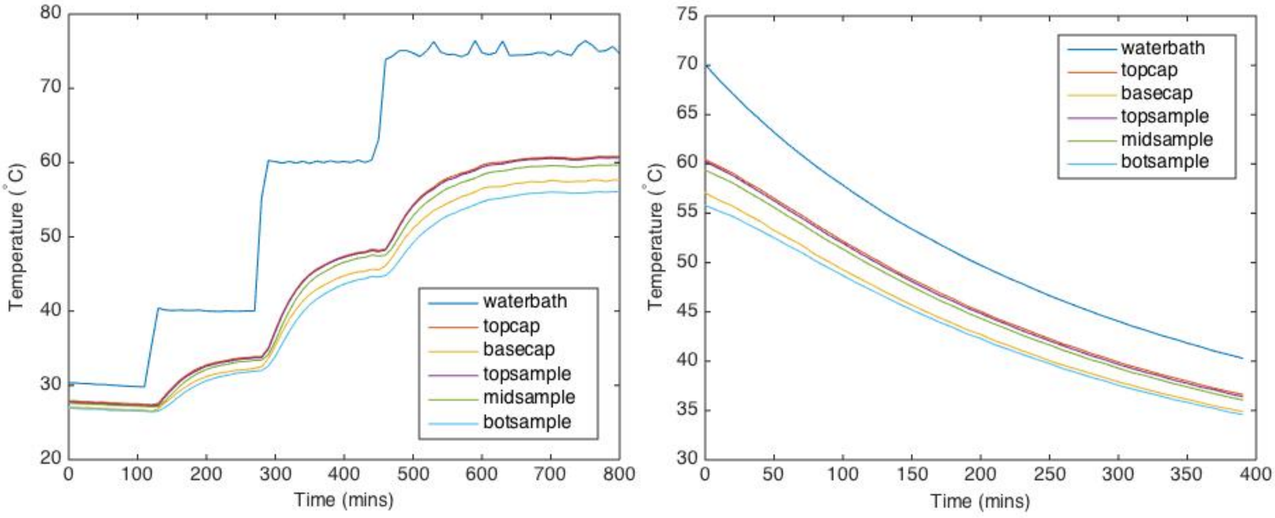
Figure 1: University of Sheffield triaxial system with temperature regulating modifications.

This study will primarily be performed on two clays with varying plasticity. One sample will be produced purely from a kaolin slurry, whilst the other will be formed from a combination of kaolin and bentonite mix at a ratio of 60:40 kaolin:bentonite by mass to provide a higher plasticity sample to that of purely kaolin [13]. Varying the plasticity of test samples will aid the understanding of the influence that plasticity and permeability contributes to a sample's response to thermal cycles. Samples will be produced by consolidating clay slurry to 500 kPa within a 250 mm diameter Rowe Cell, maintained at 20 °C. From the large Rowe Cell sample, samples of 50 mm diameter and 100 mm in height will be cut for tested. By consolidating samples to 500kPa, the samples produced will be significantly stiff, this will allow for minimal impact of the local LVDT on the samples deformation.

Following saturation, samples will be isotropically consolidated to 600 kPa within the triaxial system, at 20 °C, laboratory temperature. During shearing a mean effective stress of 500 kPa is to be applied to the sample. During the heating phase the sample will be in a drained condition. This allows for excess pore water pressure to dissipate as found by Campanella & Mitchell [9], Burghignoli et al. [14] and Cekerevac & Laloui [11]. Undrained shearing will be carried out after reaching thermal equilibrium.

Calibration of the system was initially carried out with the installation of an incompressible sample. This allowed for the local LVDT's to be tested with varying temperature to verify the manufacturer's temperature guidelines. An instrumented clay sample was then used in the calibration of heating and cooling rates (Fig. 2). This will allow testing to be carried out without the inclusion of thermocouples within actual test samples. The temperature of the top cap and base cap will be used to indicate the temperature of the sample and the heating periods required. A sinusoidal curve will be used for the heating and cooling to provide repeatability in the temperature cycles. Providing consistent and replicable heating and cooling is one of the major challenges within the study. In order to determine the time taken for the sample to reach the desired temperature, thermocouples were embedded within a consolidated kaolin sample and monitored during a staged heating phase (Fig. 2 (a)). At the time of testing, no insulation of the cell was present. This provided a baseline result for the minimum achievable temperatures within the system. It can be noted that the thermocouple embedded in the bottom of the sample is significantly cooler than the top and middle thermocouples. This was found to be due to an imperfect seal around the base cap.

Results shown in Fig. 2, indicate that it takes ~1-2 hours to achieve a temperature increment of 10-20 °C. The rate at which heating occurs within the sample is important to consider with regard to the prevention of excess pore pressures building up within the sample. Plum & Esrig [15] found that for Newfield Clay with an initial void ratio of 0.462, an increase in 20 °C produced an increase pore pressure of 100kPa on average of 5 cycles. Excess pore pressures have the potential to impact the fabric and mechanical properties of the sample, which may overshadow the impact of heating on these properties in the case of drained heating.



(a) (b)

Figure 2: Triaxial calibration curves for: (a) sample heating; (b) sample cooling.

Cooling is carried out at the rate of heat loss from the cell within a temperature-controlled 20 °C laboratory, with the pump switched off. This is the quickest method of reducing the sample temperature. Fig. 2 (b) shows the time taken for the sample to decrease in temperature.

One of the challenges is achieving staged cooling. In order to provide staged cooling, the drop in temperature must be monitored in order for the water bath heating system to be engaged to maintain a given temperature. An alternative is to decrease the water bath temperature whilst water is still circulating. However, this does increase the duration required for cooling of the sample but allows for drainage of the sample to be maintained.

The modified triaxial system will be used to investigate the shear strength of 2 clays of different plasticity (kaolin and kaolin/bentonite mixed samples), at fixed temperatures and following multiple temperature cycles. Shear strength tests at constant temperature will be carried out at 20°C, 40°C and 60°C in order to determine the differences that a direct increase in temperature has on the mechanical properties of a clay.

To build on the work carried out by Abuel-Naga et al. [10] the influence of cyclic temperature variation will be investigated on an isotropically consolidated sample. The temperature of the sample will be cycled between 25°C and 60°C for 5 and 10 repetitions, prior to shearing. This will allow an assessment of shear strength and stiffness post cyclic temperature variation to be identified in addition to any accumulated cyclic thermal deformation.

The study aims to more thoroughly understand the performance of clays under temperature changes – either through a permanent increase or through cyclic changes. The effect of cyclic temperature variation has the potential to change the shear strength and stiffness of clay. This study aims to unite an array of previous studies into one theory for predicting clay performance under temperature change, which should ultimately help guide future PFHX design.

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