Centrifuge modeling of energy foundations – effect of seasonal temperature fluctuation and soil state

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ABSTRACT: Energy foundations can reduce carbon footprint and lead to energy savings. Understanding the process of heat migration in soil is therefore of great interest in the field of geotechnical engineering. However, limited literature exists on the thermo-dynamic interaction and structural performance of an energy foundation and the surrounding soil. Lab testing of energy foundations remains inexpensive compared to field tests; however lab tests cannot easily simulate representative in-situ stress conditions. This can be resolved by using a geotechnical centrifuge to correctly mimic the stress gradient of the self-weight of the soil. A series of centrifuge models of energy foundations in different soil states (dense and loose) have been tested. Representative seasonal temperature fluctuations in the UK are used as the benchmark in this study. A total of three years of heating/cooling cycles are modelled and foundation response is captured by means of embedded temperature sensors at different distances away from the thermal foundation.

1 INTRODUCTION

Geotechnical energy structures/foundations are believed to offer potential to reducing our carbon footprint and contribute positively toward becoming a more energy sustainable society. Energy foundations serve as exchange systems to regulate building environmental conditions. As shown in Figure 1, in winter the ground temperature is higher than the air and therefore soil can provide a potential source of heat energy. Alternatively, in summer the ambient air temperature is higher than the ground temperature and the soil can be used as a heat sink to cool the building. The proposed thermal system can therefore help in reducing the reliance on conventional heating and cooling systems.

Ground energy exchange systems have been studied for many years now with Brandl (2006) reporting on the first installation of energy piles in the 1980's. Since initial deployment of such systems, design methods for their thermal or geotechnical aspects are not yet well established (Loveridge & Powrie 2012). Element tests have been employed by many researchers (Campanella & Mitchell 1968, Plum & Esrig 1969, Habibagahi 1977 and Boudali et al. 1994) to study the behaviour of heat migration in soils subjected to heating/cooling cycles. Results have indicated changes in stress, volume and strength in normally consolidated and over-consolidated soils during both heating and cooling cycles. Campanella & Mitchell (1968) showed that an increase in temperature in drained conditions produced a volume reduction of clay soil (Black et al. 2015).

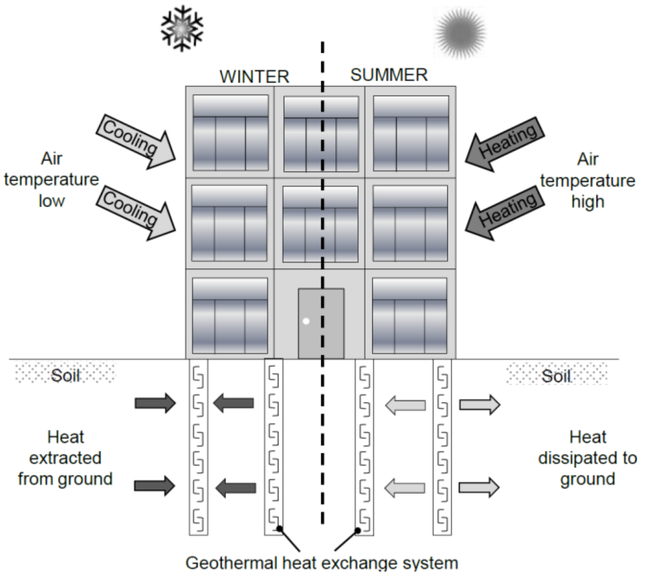

Figure 1. Concept of geotechnical energy structure (after Black et al. 2015).

Demars & Charles (1982) documented similar findings and reported that soil behaviour was strongly dependent on the over-consolidation ratio in their investigation of a marine undisturbed clay. Similarly, Towhata et al. (1993) reported that normally consolidated clays exhibited thermal contractive behaviour, whereas overconsolidated clays can show thermal dilatant behaviour. Mitchell 1964, Plum & Esrig (1969), Habibagahi (1977), and Boudali et al. (1994) also reported that the compression curves obtained at different temperatures are parallel, with lower values of void ratio at higher temperatures. The aforementioned changes in stress and strength could have considerable implications on the thermo-mechanical response of foundations (i.e. energy piles) deployed as energy structures; such that, under working stress, deterioration of stability and serviceability could manifest leading to uncertainty in long term performance (Black et al. 2015). With this in mind, a series of centrifuge tests were conducted at the Centre for Energy and Infrastructure Ground Research (CEIGR) to investigate the heat migration phenomena in soils of different density and over 3 heating/cooling cycles for a single energy pile.

2 CENTRIFUGE EXPERIMENTS

2.1 *Centre for Energy and Infrastructure Ground Research (CEIGR)*

The centrifuge used for this investigation was the newly established University of Sheffield 50gT geotechnical beam centrifuge located in the Centre for Energy and Infrastructure Ground Research. The centrifuge was designed and manufactured by Thomas Broadbent and Sons Limited, United Kingdom, and commissioned in 2014. The centrifuge beam has a radius of 2 m to the base of the swing platform, of plan area 0.8 m^2, and can accelerate a 500 kg payload to 100 gravities.

2.2 *Centrifuge scaling laws*

Geotechnical centrifuge modeling uses centrifugal acceleration to increase the self-weight stresses in a small model to equal the self-weight stresses in a large prototype. If a soil model containing the same soil as the prototype is spun at centrifugal acceleration of N times the prototype gravity, the vertical stress in a soil layer at depth h in model scale is identical to the vertical stress in the prototype soil layer of depth $N*h$. The length scaling factor (model: prototype) is therefore 1:N. Once the length scaling factor is determined, the scaling factor of volume, force, and strain can be calculated to be 1:N^3, 1:N^2 and 1:1 correspondingly.

Temperature does not vary with the increased body forces in a centrifuge; Krishnaiah and Singh (2004) confirmed that the centrifugation of a heat-flow model does not change the heat flow process (Stewart and McCartney 2014). If the thermal conductivity of the soil model and prototype are assumed to be similar, and if dimensions associated to spatial distribution of heat flow are scaled from model to prototype, then the conduction time is N^2 times faster in the centrifuge model (Stewart & McCartney 2014, Savvidou 1988, Krishnaiah & Singh 2004, Haigh 2012). Since the D_{50} of the sands (shown in next section) used in the centrifuge tests were largely smaller than 1-2mm, the influence of convection on the heat flow can be assumed to be negligible and neglected (Krishnaiah & Singh 2004, Johansen 1975, and Farouki 1986).

2.3 *Sand Properties*

The sand used in this study is named CNHST95 silica sand which is very similar to the commonly used Fraction E Leighton Buzzard silica sands. Table 1 summarizes the properties of this type of sand. The models studies in this paper were all conducted on dry sand; Krishnaiah and Singh 2004 showed that the presence of water increases the thermal conductivity of the sample (thermal conductivity of water is much greater than sand) leading to a reduction in temperature changes around the heat source.

Table 1. Properties of equivalent Fraction E silica sand used in this study.

Properties	CNHST95
D_{10}	0.100mm
D_{50}	0.139mm
D_{60}	0.150mm
e_{min}	0.514
e_{max}	0.827
G_s	2.65

2.4 *Energy pile, model setup and test matrix*

The pile was machined from aluminium bar and measured 18mm diameter by 140mm long. A cartridge heating element, 6.5mm in diameter by 70mm long, was inserted in a bored recess in the centre of the pile and fixed in place using thermal epoxy. The heating element had a power rating of 100 W and was interfaced with a CAL 3300 proportional-integral-derivative (PID) relay temperature controller that used feedback from a thermocouple embedded on the surface of the pile to regulate temperature to within 0.1°C (Black et al. 2015).

Tests were performed in an aluminium chamber, fabricated from 20mm thick plate, having internal dimensions of 200 by 200 by 460mm. The dry sand was poured into the container via a point pourer to a thickness of 430mm. The energy pile was then driven into the middle of the sand so that 120mm of it was embedded into the soil (see sensor locations outlines in Fig.2). The temperature sensors (LM135) were then placed at different radial distances from the center of the pile (1D to 3D); the sensors were all embedded at a depth of 60mm (middle of the embedded energy pile). Two Linear Variable Differential Transformers (LVDT) were placed at about 3D away from the pile to monitor potential surface settlement/dilation during heating/cooling cycles. This research study focuses on the heat flow in soil, effect of soil density and response of the temperature sensors during different heating/cooling cycles.

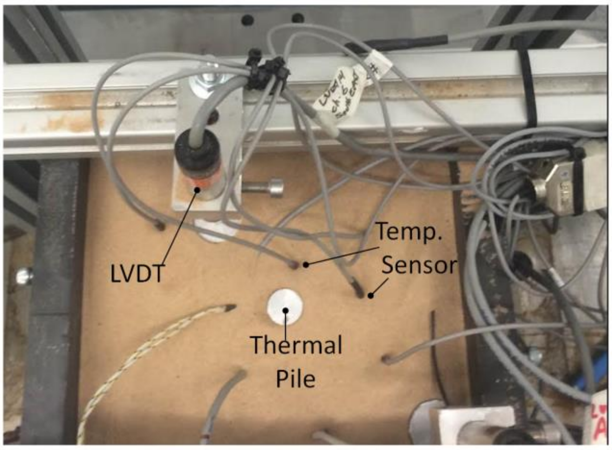

Figure 2. Sensor locations for the current study including a energy pile, 2 LVDT's and 8 temperature sensors at different radial locations from the center of the pile.

A series of two tests were conducted using the CNHST95 sand to study the effect of sand state (dense versus loose) on the heat migration. The dense state had a relative density of 93% while the loose soil had a relative density of 55%. To simulate the building load, a constant prototype scale axial load of 900 kN and 250 kN were applied to the thermal foundation in dense and loose soil respectively (a factor of safety of about 5). All models were tested at 50 times gravitational acceleration (50g) where a 3 month heat cycle equates to approximately 50 minutes in the centrifuge (1:N^2 scaling law for heat flow through conduction). Both models were exposed to three equivalent years of heating/cooling as depicted in Figure 3. The settlement occurred during initial loading and during heating/cooling cycles was negligible.

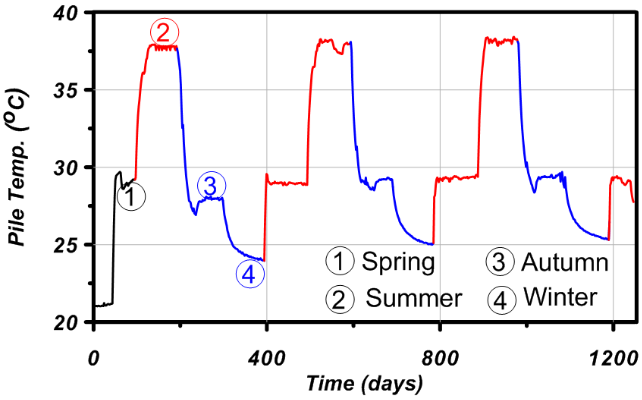

Figure 3. Seasonal temperature fluctuations considered in this research study. Heating cycles are noted in red and cooling cycles in blue. Note that a scale factor of N^2 was used for conduction heat flow time.

Seasonal temperature fluctuations in the UK are used as the benchmark in this study. The proposed temperature cycle starts with 1.5 month of spring at temperatures around 29°C followed by a 3 month summer of temperatures around 38°C. The summer is followed by a 3 month autumn where average temperature is back to 29°C and is followed by a 3 month winter of temperatures around 23°C. Lastly, the remaining 1.5 month of spring is modeled where temperatures are back to 29°C. Each cycle then consists of two heating periods (spring to summer and winter to spring) and two cooling periods (summer to autumn and autumn to winter).

As shown in Figure 3, the achieved winter temperatures increased slightly from 24°C in the first cycle to 25°C and 25.5°C in the next two cycles. The cooling system relies entirely on self-cooling as the energy source is turned off. The centrifuge chamber undergoes a background increase in temperature during spinning; the amount of increase is more during long duration tests. Cox et al. (2016) demonstrate the change in temperature and relative humidity for different centrifugal accelerations and test duration during the development of a centrifuge health monitoring system. A temperature sensor monitoring the chamber temperature change was used during this study and the variation of chamber temperature with time (scaled by N^2) is plotted in Figure 4. The chamber temperature experienced an increase in temperature of about 6.5°C during the 11.5 hours of spinning time (model scale). Stewart & McCartney (2014) reported an increase in chamber temperature of about 4°C in their experiment where total spinning time was about 7 hours and attributed it to the friction of the centrifuge moving through the air inside the centrifuge chamber.

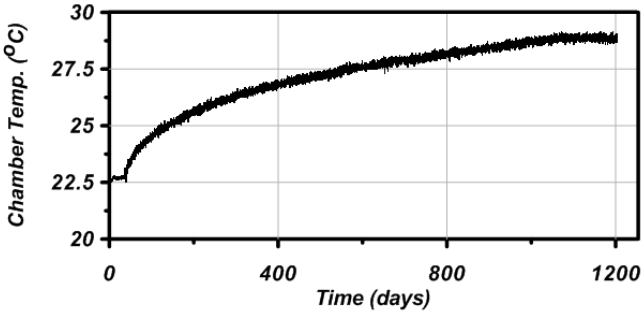

Figure 4. Variation of chamber temperature with time during centrifuge spinning. Note that time is scaled by N^2 to equate the prototype time used for conduction heat flow. Actual spinning time is about 11.5 hours.

3 RESULTS

3.1 *Effect of radial distance away from the heat source*

Figure 5a plots the temperature response of the energy pile and the surrounding temperature sensors located at different radial distances from the energy pile (1D, 2D and 3D) for the dense sand condition during the entire three year heating/cooling regimes. Figures 5b and 5c plot the response of the energy pile and the temperature sensors in the 1st heating and cooling regimes only. As shown in Figure 5a, the soil temperature lags behind the temperature oscillations in the energy pile. This can be attributed to the heat flow process where with increasing distances away from the energy pile, the sensors show an increased lag behind the thermal temperature. Stewart & McCartney (2014) and Krishnaiah & Singh (2004) also reported similar lag effect in the response of sensors mounted in soil at different distances away from the energy pile. Figure 5a also shows that temperatures in soil did not reach the same temperatures as the energy pile; temperature in soil further away from the thermal source experienced less increase in temperature. The temperature in soil experienced a maximum incremental increase in temperature of 4°C (at 1D) and an incremental reduction in temperature of 2.5°C (also at 1D) while the energy pile had a change of temperature (both increase and decrease) of about 9°C.

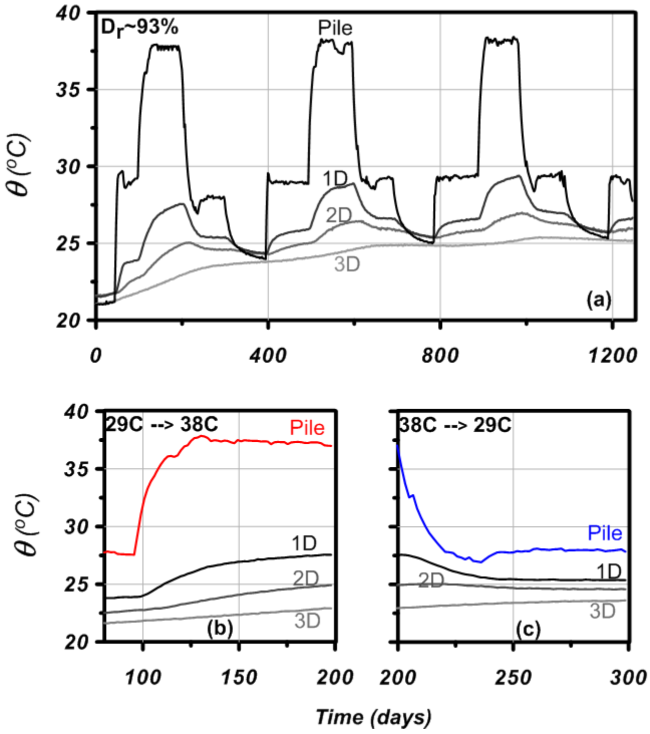

Figure 5. Temperature variation of energy pile and temperature sensors at different radial distances away from the energy pile in the *dense* sand test, 5a complete 3 year cycle, 5b 1st heating regime (spring to summer) and 5c 1st cooling regime (summer to autumn).

Figure 6 plots the energy pile and temperature sensor response for the loose sand condition. Similar to results shown in Figure 5, it can be seen that the magnitude of change in temperature reduces in soil with increasing distances away from the thermal source. Also, the temperature response in the soil lags behind the heat source and soil furthest away experiences the most lag. The temperature in soil experienced a maximum increase in temperature of 6.5°C and a reduction in temperature of 4.5°C while the energy pile had a change of temperature (both increase and decrease) of about 9°C. The temperature in soil at 2D away from the thermal source degrades less significantly than the soil near the thermal source (1D away) shown in Figure 6c; the temperature of soil 3D away from the heat source does not show any degradation during cooling cycles and seem to saturate and reach a plateau instead. The time required for the soil at further distances away from the thermal source (> 2D) to cool down seems to be greater than the total time allowed in the test series and soil reaches a plateau instead due to the stoppage of the heat source; this amount of change is also larger than the change in the dense sand condition. This effect will be studied in more detail in the next section.

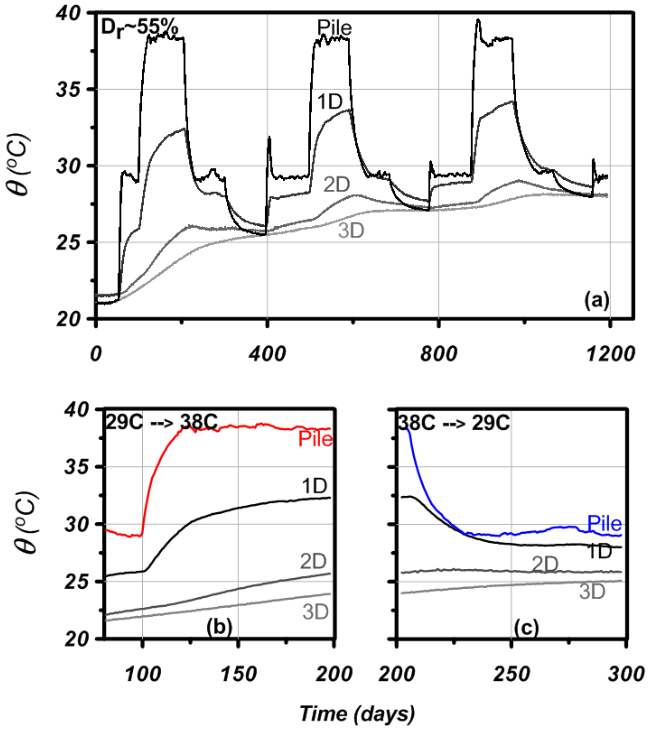

Figure 6. Temperature variation of energy pile and temperature sensors at different radial distances away from the energy pile in the *loose* sand test, 6a complete 3 year cycle, 6b 1st heating regime (spring to summer) and 6c 1st cooling regime (summer to autumn).

3.2 *Percentage increase in temperature, μ*

Krishnaiah & Singh (2004) defined the percentage increase in temperature (μ) as shown in Equation 1.

$$\mu = -[1-\frac{\theta}{\theta_o}] \qquad (1)$$

where θ is the incremental temperature and θ_o the initial temperature. In heating regimes μ will be positive ($\theta > \theta_o$) and in cooling regimes it will be negative ($\theta < \theta_o$) indicating a reduction in temperature. From Equation 1 it is apparent that a larger incremental temperature (given the initial temperatures are held constant) will lead to a smaller μ.

Parameter μ can be reported as a continuous change in temperature or it could be measured at the end of each season (heating and cooling regimes) throughout heating/cooling regimes and for different radial distances away from the heating source (Krishnaiah & Singh 2004).

3.3 *Effect of relative density on μ*

Figure 7 plots the temperature response of soil at a distance of 1D away from the thermal source for the dense and loose condition, and compares them with the temperature of the thermal source. It should be noted that the initial temperature (θ_o) of each sensor plotted in Figure 7 was chosen at the point just before the start of the first heat regime. The y-axis then measures the total change in μ with respect to θ_o throughout the plot.

It is apparent from Figure 7 that the dense sample (higher density sample shown in lighter grey) leads to smaller values of μ (measured continuously as shown in Figure 7). This reflects that higher density samples are better in conduction; the thermal conductivity of the dense sample is therefore higher than the loose sample. Krishnaiah & Singh (2004) also reported similar patterns and attributed the increased thermal conductivity of the dense sample to the improved contact between the soil grains in dense sand condition.

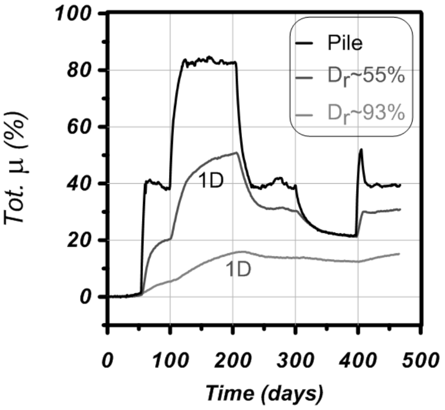

Figure 7. Effect of sample state (dense versus loose) on heat migration.

3.4 *Effect of seasonal temperature oscillation on incremental μ*

Incremental μ can be calculated for each heating/cooling regime where θ_o will be taken as the temperature just before start of the heating/cooling regimes. For example, θ_o for the heating regime of 29°C to 38°C will be 29°C. Figure 8 plots the incremental μ for the two heating regimes (29°C to 38°C and 24°C to 29°C) and two cooling regimes (38°C to 29°C and 29°C to 25°C) of the dense sample and for all three cycles. Figure 9 plots the same incremental regimes but for the loose sand condition. It should be noted that at certain distances away from the thermal source (e.g. 2.5D and 3D), more than one temperature sensor was available and results plotted in Figures 8 reflect all sensor readings. Effect of distance away from the heat source as discussed and shown before is also apparent in Figures 8 and 9 as the magnitude of incremental μ is always larger in smaller distances away from the heat source (regardless of heating or cooling conditions).

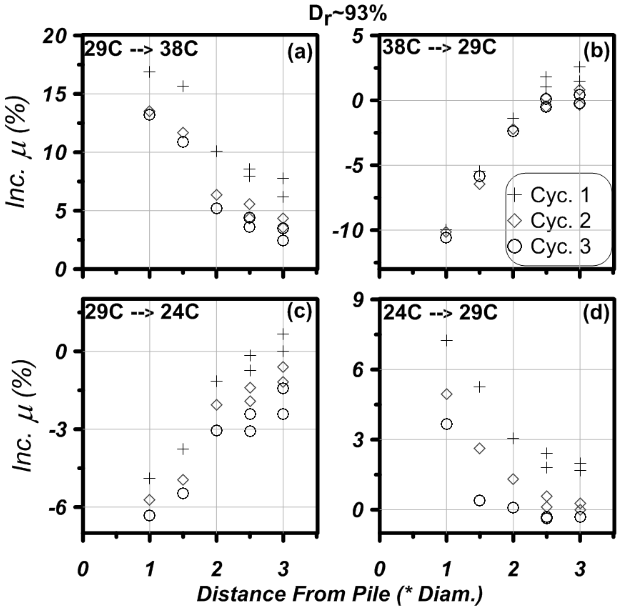

Figure 8. Effect of seasonal temperature oscillations on the incremental μ for the dense sand condition.

Figure 8a shows that the incremental μ in cycle 1 lies slightly (less than 5%) above cycles 2 and 3 and there is no significant change in μ during second and third cycles. This reflects that the ground acted better in conduction in second and third cycles than in the first cycle. Upon first cooling regime (Figure 8b) the incremental μ becomes negative (reduction in temperature) in the areas being 3D or closer to the heat source. The soil closer to the heat source (1D) loses up to 10% of its temperature compared to its final temperature in summer. The soil further in distance either does not change in temperature or slightly undergoes increase in temperature (from the previous heating regime). The 3 month cooling period in autumn is therefore not long enough for the soil in further distances (> 3D) to undergo cooling (given a heat regime existed prior to cooling). During winter and as shown in Figure 8c, the ground continues to reduce in temperature; distances closer to the heat source continue loosing temperature up to 6% when compared to its final temperature in autumn. There is a slight (1-3%) difference between the incremental μ for cycles 1, 2, and 3; this slight change can perhaps be considered negligible. The difference in μ for different cycles is more pronounced in the last heating regime where distances closer to the heat source (< 2D) alter in μ up to 7%.

Figure 9 plots the incremental μ for different heating cooling regimes similar to Figure 8 but for the loose sand condition. The larger value of μ in every regime especially closer to the heat source is apparent. The difference in μ for different cycles remains small (0.5-3.5%) except for the last heating regime, where a difference in μ of up to 7% is evident, similar to the dense sand condition.

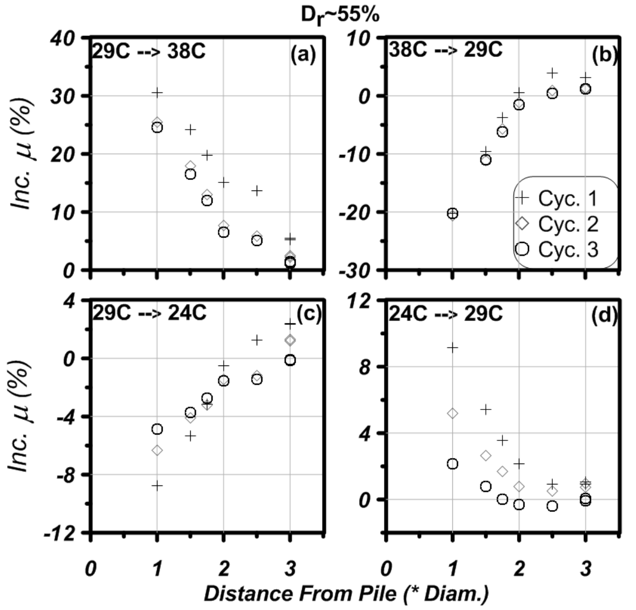

Figure 9. Effect of seasonal temperature oscillations on the incremental μ for the loose sand condition.

Bourne-Webb et al. (2009) reported that the temperature recorded in a borehole positioned 0.5 m from the energy pile halved at a radial distance equivalent to 1D and at 1.5D changes were negligible. Cui et al. (2011) reported 1.2D for the zone of influence from a numerical analysis of a pile geothermal heat exchanger. Black et al. (2015) also reported a zone of influence of 1.5D using transparent soils. The results of the present study show that regardless of the previous number of heating/cooling regimes, magnitude of the incremental μ remains less than 10% at a distance greater than 1.5D for dense sand and greater than 2.5D for loose sand.

4 CONCLUSIONS

Two centrifuge tests of thermal foundation experiments were run on dry sands of different densities. Centrifuge scaling laws for heat flow through conduction were used to model three years of heat flow in the centrifuge considering two heating and two cooling regimes in each year. Results reveal that the denser sand acts as a better conductor of heat and therefore percent change in temperature at different distances away from the heat source remains smaller than the loose sand. This difference is more pronounced in the areas closer to the heat source (< 1.5D).

Effect of previous heating/cooling regimes on the change of temperature is also investigated in the present study. In a dense sand environment, it is found that the change in temperature remains less than 10% at distances greater than 1.5D. In a loose sand state, the change in temperature is less than 22% in distances closer than 1.5D and is less than 10% at distances greater than 2.5D.

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