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Response of shallow geothermal energy pile from laboratory model tests

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Abstract. In shallow geothermal energy pile systems, the thermal loads from the pile, transferred and stored in the soil will cause thermally induced settlement. This factor must be considered in the geotechnical design process to avoid unexpected hazards. Series of laboratory model tests were carried out to study the behaviour of energy piles installed in kaolin soil, subjected to thermal loads and a combination of axial and thermal loads (henceforth known as thermo-axial loads). Six tests which included two thermal load tests (35°C and 40°C) and four thermo-axial load tests (100 N and 200 N, combined with 35°C and 40°C thermal loads) were conducted. To simulate the behaviour of geothermal energy piles during its operation, the thermo-axial tests were carried out by applying an axial load to the model pile head, and a subsequent application of thermal load. The model soil was compacted at 90% maximum dry density and had an undrained shear strength of 37 kPa, thus classified as having a firm soil consistency. The behaviour of model pile, having the ultimate load capacity of 460 N, was monitored using a linear variable displacement transducer, load cell and wire thermocouple, to measure the pile head settlement, applied axial load and model pile temperature. The acquired data from this study was used to define the thermo-axial response characteristics of the energy pile model. In this study, the limiting settlement was defined as 10% of the model pile diameter. For thermal load tests, higher thermal loads induced higher values of thermal settlement. At 40°C thermal load an irreversible settlement was observed after the heating and cooling cycle was applied to the model pile. Meanwhile, the pile response to thermo-axial loads were attributed to soil consistency and the magnitude of both the axial and thermal loads applied to the pile. The higher the thermo-axial loads, the higher the settlements occurred. A slight hazard on the model pile was detected, since the settlement occurred was greater than the limiting value when the pile was loaded with thermo-axial loads of 40°C and 200 N. It is therefore recommended that the global factor of safety to be applied for energy pile installed in firm soil should be more than 2.3 to prevent any hazard to occur in the future, should the pile also be subjected to thermal load of 40°C or greater.

1. Introduction

The shallow geothermal energy pile system is a type of sustainable geostructure technology that is designed to achieve energy efficient space heating and cooling, for residential and commercial buildings; while satisfying load bearing requirements of the underlying foundation [1]. The mechanism of a geothermal energy pile system uses its surrounding soil as an intermittent energy storage medium. A normal pile foundation may be converted into a geothermal energy pile by incorporating a heat exchanger pipes containing heat exchanger fluids. As such, the heat exchanger piles are able to facilitate the transportation of ground thermal energy from buildings to the soil (and vice versa) via these heat exchanger pipes embedded in the piles [2][3].

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Nowadays, the geothermal energy pile system has been implemented all around the world, for example in Austria [4], Switzerland [5], United Kingdom [6], Japan [7] and China [1]. Even though the use of this sustainable geostructure has gained acceptance in the said countries, the engineering community has reservations with regards to the effect of thermal loads on the performance of this system during its operation. This concerns stems from the limited knowledge of the performance for this system, and also the absence of an established geotechnical design method designed specifically for this novel technology.

In recent times, the behavior of the geothermal energy piles under thermal loads, and coupled axial and thermal loads (thermo-axial loads) has been the subject of research of European, North American and Asian researchers alike. Some physical model research endeavors include full-scale testing of energy piles conducted by [4], [5] and [6], centrifuge tests conducted by [8] and [9], and single gravity laboratory model testing conducted by [10] and [11]. Meanwhile, the numerical models of energy pile systems, particularly on soil-structure interaction were developed by [12], [13] and [14] in order to obtain a deeper understanding of the geothermal energy pile behaviour under operational conditions. For the purpose of this study, the laboratory tests on model of shallow geothermal energy piles were able to give an insight on the performance of energy piles in a tropical weather condition found in the Malaysian environment. This paper presented the effect of thermal loads on the behavior of energy piles based on laboratory model tests on firm kaolin soil. The study had focused on the thermally-induced settlements in order to quantify the effects of additional thermal loads imposed on axially loaded energy piles.

2. Materials and Methodology

This section presents the soil material and research methodology used in this study, by describing the laboratory work carried out to achieve the aim and objectives.

2.1. Material

In order to investigate the behaviour of energy piles using laboratory model, commercially available kaolin soil was used. Prior to the start of the main testing stage, relevant standard laboratory tests were conducted to obtain the basic properties and undrained shear strength of the compacted cohesive soil. The laboratory test results are shown in Table 1.

Table 1. Physical Indices of Kaolin soil

Parameter	Soil Type	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Specific Gravity (G_s)	USCS Classification
Description/ Value	Cohesive Soil	38	27	11	2.64	ML

The kaolin soil used for this study was similar to that used by [8] and [9], since both researchers had used the soil that was classified also as ML. Furthermore, the S300 kaolin soil was chosen for this study because it possesses a high fines content to enable the observation of thermal consolidation and low plasticity to prevent changes in soil-pore water interactions due to temperature changes, as stated by [9]. Meanwhile, the standard Proctor compaction test had shown that the soil used in this study had a

maximum dry density (MDD) value of 1.63 Mg/m^3 , with an optimum moisture content (OMC) value of 17%.

2.2. Experimental Setup

In general, model pile tests are commonly used to study soil-structure interaction mechanism by allowing researchers to assess the behaviour of model piles in a controlled environment [10]. The size of the energy pile laboratory model developed for this study was quite similar to that developed by [9] and [15], but slightly smaller than the model developed by [11]. Moreover, the laboratory models developed by the said researchers were meant for tests conducted with cohesionless soils, while this study used cohesive soil instead.

As such, this laboratory model pile test in single gravity conditions was developed to determine the behavior of a model energy pile subjected to thermal and thermo-axial loads in cohesive soil. The laboratory model energy pile test system comprises of four (4) components, namely the axial load control system, thermal load control system, soil container and the model pile.

In particular, the axial load control system comprised of a stress-controlled system provided using a pneumatic cylinder, while the load applied to the model pile head was monitored using a load cell. The thermal load system consisted of a metallic U-tube that was installed within the model pile length to emulate a uniform temperature distribution, which was then connected to a temperature bath to enable the thermal load to be controlled.

Meanwhile, the model of soil and the model energy pile assembly was designed by scaling down an energy pile found in practice. The typical value of energy pile diameter ranges from 0.6 to 1.5 m, while the pile length ranges from 10 to 25 m [15]. For the purpose of this study, a representative energy pile prototype with a diameter of 1.35 m and length of 13.5 m was chosen. Therefore, the model foundation chosen for this study was made of stainless steel with a diameter of 15 mm and 150 mm embedded length. Figure 1 shows the prototype and model dimensions while the soil chamber used in this study is shown in Figure 2.

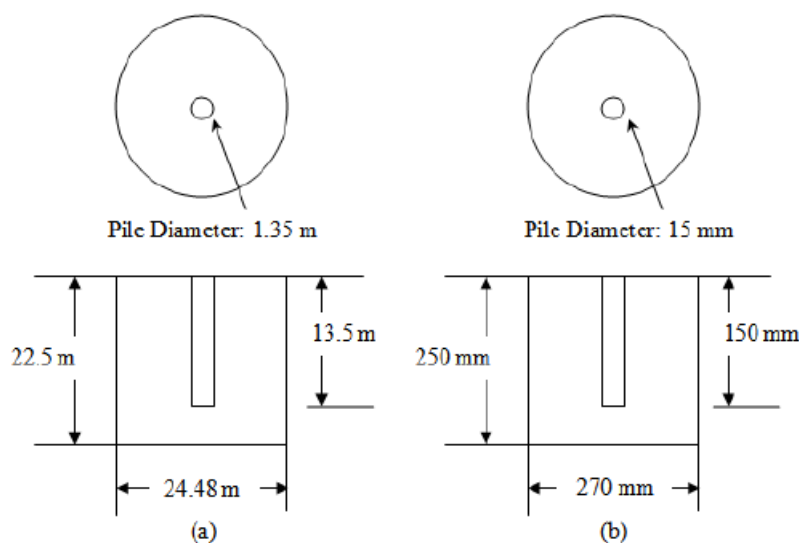


Figure 1. Soil and energy pile dimensions: (a) Prototype and (b) Model



Figure 2. Soil chamber

2.3. Experimental Method

To prepare the soil model, the S300 kaolin powder was oven dried at 105°C for 24 hours to prevent any biological activity within the sample, as explained by [16]. The model pile was fixed in the centre of a 270 mm inner diameter cylindrical acrylic plexiglass, while the model soil was compacted around the pile by using a steel tamper. The chosen target dry density was 1.39 Mg/m³ (corresponding to a relative density of 90%). In this type of pile installation, the method chosen to install the model pile was similar to that of the installation of non-displacement piles [4].

Through the loading test conducted on the model pile, it yielded an ultimate bearing load of 460 N. The ultimate load was used to calculate the actual factors of safety (FOS), based on the chosen values of axial loads used in this study, which were 100 N and 200 N. The global factor of safety was then calculated by dividing the ultimate load with the axial loads imposed on the pile head, as shown in Table 2.

Table 2. Factor of safety for imposed axial loads

Ultimate Load	Axial Load	
	100 N	200 N
460 N	4.6	2.3

Next, the undrained shear strength of the model soil were obtained by carrying out the unconfined compression tests (UCT) on the prepared model soil. Standard UCT were conducted on samples with 38 mm diameter and 76 mm height. The average undrained shear strength obtained was about 37 kPa and the average water content of the soil was about 17%.

Upon the completion of the model pile and soil preparations, the experimental equipment (temperature bath, load cell and LVDT) were setup, followed by the application of the axial load and finally the application of the thermal loads (one cycle of heating and cooling). All observed data were recorded on a data logger. To measure the vertical displacement of the model pile, an LVDT was set on a steel plate fixed to the pile head. A total of two thermal load tests and four thermo-axial load tests were performed.

For thermal loads series (chosen temperature values were 35°C and 40°C), no axial loads were applied on the model pile. The reason behind choosing the 35°C and 40°C for the thermal load values stems from the typical conditions where energy piles are subjected to thermal loading with temperature varying in the range between 0-50°C [4].

In the thermo-axial load tests, the chosen axial loads (100 N and 200 N, representing working loads with the application of global FOS of 4.6 and 2.3 respectively to the ultimate load) were applied first. The thermal load was applied immediately after the settlement of the soil due to axial loading has remained constant. The thermal cycle consists of increasing the pile temperature to 35°C and 40°C from the room temperature (approximately 27°C), and subsequently reduced back to 27°C. Only one thermal cycle was applied for each test.

3. Experimental Results and Discussion

This section features the results and analysis of tests conducted. As previously mentioned, laboratory tests were carried out to determine the physical and the mechanical properties of the S300 kaolin material, followed by the thermal load and thermo-axial load tests on the model piles. Results of the tests on the energy pile models were presented and analyzed, based on the varying thermo-axial loads.

3.1. Thermal Load Test

Heat transfer through soils is through soil grains, water, and pore air. Yet, the transfer mainly occur through the soil particles, owing to the much higher thermal conductivity of the solids relative to the water and air. In general, increase in temperature will result in thermal expansion of soil grains as well as pore fluid [17]. Hence, the soil will heave as the temperature increases and settle as the temperature decreases. However, the results from this study shown in Figure 3 reveals a different trend. The experimental data obtained from the thermal load tests showed a downward trend of the pile head settlement. It is also observed that the pile response appeared to be thermo-elastic [18] in which the settlement increased as the temperature increased but decreased back to almost the same value as the temperature was reduced during the cooling period.

The results of the said thermal load tests seemed to contradict the findings of which where the pile was not axially loaded, the results show pile head heave during heating, and settlement during cooling [10], [12] and [19]. This is because when a heating cycle is applied to a pile, it expands, and any axial deformation will be opposed by shaft restraint at the soil-pile interface. Furthermore, the expansive deformations generate a "negative" shaft friction, whereby the pile expands up relative to the surrounding soil over the upper half of the pile [19]. Consequently, it is in agreement with the outcome of the thermal load test conducted by [10]. They concluded that the thermal strains generated consistently negative (expansive) strains on the pile head during heating, since it is permitted to freely expand upward under the constant applied thermal load.

For the thermal loading test series in this study, there should not be any axial load imposed on the model pile. Upon checking, it was detected that the pile was packed with the load application system before subjected to thermal load. Residual axial loads contributed from the model pile cap and load plunger, both placed directly on the model pile head may have inadvertently contributed to the initial axial loads. As stated by [5] and [6], the dilation of the model pile during heating causes additional stresses to be developed at the pile toe, which eventually induces the thermal settlement. This is in agreement with the results obtained from this study.

The designated limiting settlement was defined as 10% of the model pile diameter, which amounts to 1.5 mm. Results showed that the maximum settlement for the model pile heated to 40°C only reached a value of 0.14 mm, while the maximum settlement for the model pile heated to 35°C reached a value of 0.1 mm. Hence, both thermal settlement values were observed to be relatively small, which were less than 1% of the pile diameter. An hysteresis phenomenon [11], that was a distinct heating and cooling paths, was also observed in the cycle. Consequently, the irreversible thermal settlement phenomenon that was observed during the cooling cycle of the 40°C thermal load was in line with the findings of [5] and [6]. However the value was only 0.01 mm (less than 0.1% of the pile diameter), which could be considered as negligible.

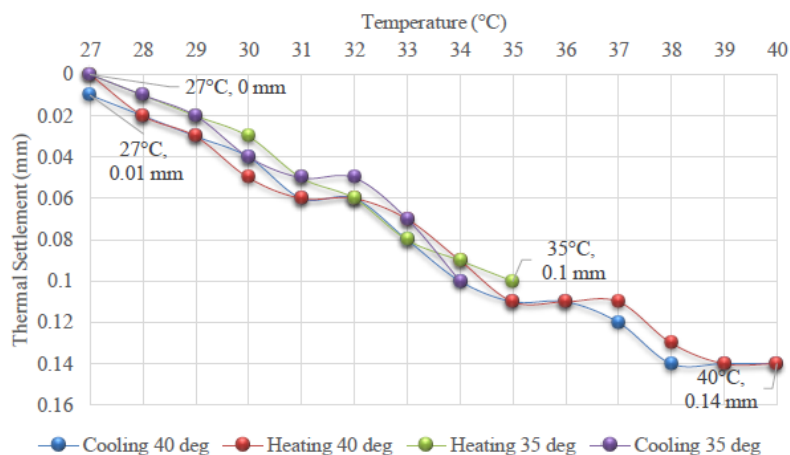


Figure 3. Model pile head settlement due to thermal load at 35°C and 40°C

3.2. Thermo-Axial Load Test

The thermo-axial settlements due to thermal load of several combinations of both axial and thermal loads were shown in Figure 4. The thermo-axial settlement at 35°C thermal load, where combined with an axial load of 100 N yielded 0.67 mm, while for axial load of 200 N the settlement produced was 0.87 mm. Similarly, for the thermo-axial settlement at 40°C thermal load, when combined with an axial load of 100 N the resultant settlement was 1.34 mm, and for the 200 N axial load the settlement amounted to 1.54 mm. It was found that only one thermo-axial settlement exceeded the limiting settlement (1.5 mm), which was the 200 N axial load combined with 40°C thermal load.

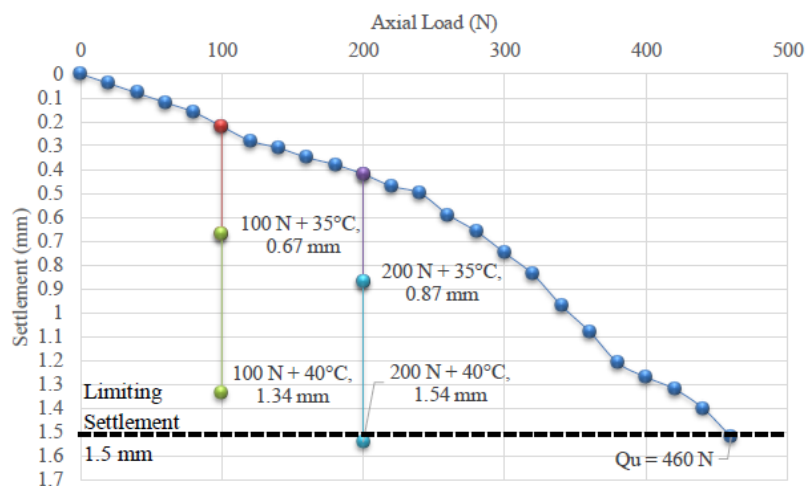


Figure 4. Thermo-axial settlements with respect to settlement at ultimate load

Results showed in Figure 4 indicated that the global FOS of 2.3 applied to the ultimate load was found to be deemed not adequate if the pile was also to withstand thermal load of 40°C or more. Therefore, it could be recommended that for high thermal loads (40°C or more), the working load for geothermal pile should be reduced, hence applying higher FOS. This is to accommodate the effects of thermally induced settlements, which were observed to give a greater damaging effect when combined with axial loads, hence the failure hazard could be prevented. The global FOS to be applied on energy pile installed in firm kaolin soil should be more than 2.3 to ensure that the thermo-axial settlement does not exceed the limiting value.

Based on the plotted graphs in Figure 4, generally the thermo-axial settlement curve was somewhat similar to the thermal settlement curve that indicated a steady downward trend as the heat was gradually transferred from the pile to the soil. As stated by [19], the pile response to thermal loads and thermo-axial loads are attributed mainly to ground conditions, end restraint conditions and the magnitude of thermal load applied to the pile. The initial axial load contributes additional stresses at the pile toe, which was reflected in the larger values of thermo-axial settlement, compared to the thermal settlement alone.

Reflecting back on the thermal loading results, there was the needs for addressing the limitation of the current experimental setup. As such, on-going research works will focus on eliminating possible sources of shock loads and initial loads during the experimental setup.

4. Conclusion

In this study, the behaviour of geothermal energy pile model embedded in firm cohesive soil, subjected to varying thermal load and thermo-axial loads were determined using a single gravity laboratory model tests. Although some limitation occurred in the study but the results could provide an insight on the behavior of energy piles, since the current state of knowledge regarding this novel technology is limited, particularly in Malaysia. A total of six tests were performed on kaolin clay compacted to 37 kPa undrained shear strength, to evaluate the behavior of the energy pile model under different thermo-axial loads. The thermal loads of up to 40°C induced very small values of thermal settlement, whereby it was less than 1% of the pile diameter. The irreversible thermal settlement phenomenon was also observed

during the cooling cycle of the 40°C thermal load. The model pile's response subjected one cycle of heating and cooling was also appeared to be thermo-elastic.

Meanwhile, the pile response to thermo-axial loads were attributed to soil consistency and the magnitude of both the axial and thermal loads applied to the pile. The higher the thermo-axial loads, the higher the settlements occurred. It can be concluded that the global factor of safety (FOS) of 2.3 applied to the ultimate bearing capacity was found to be deemed not adequate if the pile was also to withstand 40°C thermal load or more. Hence to avoid hazard due to large settlement, a greater FOS is necessary.

In view of the limitation of this study, future research considerations include the addition of thermocouple strain gauges to monitor the strain changes along the model pile, and investigating the effects of several thermal cycles on the behavior of energy piles models to represent a better simulation of the actual operational conditions of a geothermal energy pile system.

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