PERFORMANCE OF GEOTHERMAL ENERGY PILES UNDER THERMO-AXIAL LOADS

ADRIANA ERICA AMALUDIN

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For

My Father, Amaludin Sagi and My Mother, Latifah Yacob

&

My Brothers, Hassanel Zachary Amaludin and Nazrein Adrian Amaludin

For their love, support, encouragement and prayers

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ABSTRACT

The geothermal energy pile system is a sustainable geostructure system designed to meet the cooling demands of a building by storing excess heat from the building into the soil, acting as a heat sink. Thermal loads stored in the soil will cause thermally induced settlement, and this factor must be considered in the geotechnical design process. This study aims to develop a preliminary geothermal energy pile laboratory testing system in single gravity condition, to produce the load-settlement curves generated by thermo-axial load tests. The model energy pile behaviour was studied using a physical model consist of a soil container (450 mm height and 270 mm diameter), model pile (15 mm diameter and 150 mm embedded length), and an axial and thermal load control system provided by a pneumatic cylinder and a temperature bath, respectively. Axial loads (100 N and 200 N), thermal loads (35˚C and 40˚C) and combinations of both loads (thermo-axial loads) were applied to the model pile. The axial load values were chosen based on the ultimate capacity of the model pile in soft soil (about 0.5 and 0.25q_u). The kaolin soil used during model testing was classified as silt of intermediate plasticity (MI). The model soil was compacted at 80% and 90% maximum dry density, which were classified as having soft and firm consistency. The model pile behaviour was monitored with a linear variable displacement transducer, load cell and wire thermocouple connected to a data logger to monitor the pile head settlement, applied axial load and pile temperature. The pile response to thermo-axial loads appears to be thermo-elastic and is attributed to soil consistency and magnitude of thermal load applied to the pile. Thermal loads induced small settlement values, whereby the highest value was about 1% of the pile diameter (0.15 mm). In general, firm soils produce lower thermally induced settlement, due to higher restraint at the pile head compared to soft soils. For 35˚C thermal loads, the resulting settlement did not exceed the limiting settlement, which is defined as 10% of the model pile diameter (1.5 mm). The highest thermo-axial settlement obtained was 1.66 mm for thermo-axial load of 40°C and 200 N (global factor of safety (FOS) of 1.9) in soft soil, and the settlement at 100 N axial load (global FOS of 3.8) amounts to 1.59 mm. Consequently, in firm soil and for thermo-axial load of 40˚C and 200 N (global FOS of 2.3), the thermo-axial settlement is 1.54 mm. To ensure that the thermo-axial settlement does not exceed the limiting settlement, the recommended global FOS used for soft soil and firm soil should be more than 4.0 and 2.5, respectively. A laboratory scale model of an energy pile system, specifically for cohesive soils in single gravity conditions has been developed. This laboratory model is able to produce reliable thermo-axial load-settlement curves in varying soil consistencies, initial axial loads and also varying thermal loads.

ABSTRAK

Sistem cerucuk tenaga geoterma adalah satu sistem geostruktur lestari yang direka untuk penyejukan bangunan dengan menyimpan haba yang berlebihan dari bangunan itu ke dalam tanah yang bertindak sebagai sinki haba. Beban haba yang disimpan di dalam tanah akan menyebabkan enapan terma, dan faktor ini perlu dipertimbangkan dalam proses reka bentuk geoteknik. Kajian ini bertujuan untuk menghasilkan sistem pengujian makmal cerucuk tenaga geoterma peringkat permulaan di dalam keadaan graviti tunggal, bagi menghasilkan lengkuk beban-enapan yang diperolehi daripada ujikaji terma-paksi. Sifat model cerucuk tenaga telah dikaji dengan menggunakan model fizikal yang terdiri daripada bekas tanah (450 mm tinggi dan 270 mm diameter), model cerucuk (15 mm diameter dan 150 mm kedalaman terbenam), serta sistem kawalan beban paksi dan suhu yang dihasilkan masing-masing oleh silinder pneumatik dan kubang suhu. Beban paksi (100 N dan 200 N), beban terma (35˚C dan 40˚C) dan gabungan kedua-dua beban (beban terma-paksi) telah dikenakan kepada model cerucuk tersebut. Nilai beban paksi yang dipilih adalah berdasarkan nilai kapasiti muktamad model cerucuk di dalam tanah lembut (kira-kira 0.5 dan 0.25q_u). Tanah kaolin yang digunakan untuk ujian model diklasifikasikan sebagai kelodak berkeplastikan pertengahan. Tanah model dipadatkan pada tahap 80% dan 90% ketumpatan kering maksimum dan diklasifikasikan sebagai mempunyai kekonsistenan lembut dan kukuh. Kelakuan model cerucuk dipantau menggunakan transducer anjakan linear boleh ubah, sel beban dan wayar termogandinganyang disambungkan kepada alat pencatat data bagi memantau enapan kepala cerucuk, beban paksi dan suhu cerucuk. Tindak balas cerucuk kepada beban terma-paksi adalah termo-elastik, yang bergantung kepada kekonsistenan tanah serta magnitud beban terma yang dikenakan kepada cerucuk. Beban terma menghasilkan nilai enapan yang kecil, di mana nilai enapan terma tertinggi adalah kira-kira 1 % daripada nilai diameter cerucuk (0.15 mm). Secara amnya, tanah kukuh akan menghasilkan enapan terma teraruh yang lebih rendah daripada tanah lembut disebabkan oleh tahap kekangan yang tinggi di kepala cerucuk. Bagi beban terma 35˚C, enapan terma dan terma-paksi tidak melebihi enapan penghad yang ditetapkan sebagai 10% nilai diameter cerucuk (1.5 mm). Nilai enapan terma-paksi tertinggi adalah 1.66 mm bagi beban terma-paksi 40°C dan 200 N, (nilai faktor keselamatan (FOS) global adalah 1.9) di dalam tanah lembut, manakala enapan pada 100 N beban paksi (nilai FOS global adalah 3.8) memberi nilai sebanyak 1.59 mm. Selain itu, di dalam tanah kukuh, bagi beban terma-paksi 40˚C dan 200 N (nilai FOS global sebanyak 2.3), nilai enapan terma-paksi adalah 1.54 mm. Untuk memastikan bahawa nilai enapan paksi-terma tidak melebihi enapan penghad, nilai FOS global yang disarankan bagi tanah lembut dan tanah kukuh masing-masing adalah lebih besar daripada 4.0 dan 2.5. Sebuah model berskala makmal bagi sistem cerucuk tenaga, khas untuk tanah jeleket di dalam keadaan graviti tunggal telah dihasilkan. Model ujikaji ini mampu menghasilkan lengkuk beban-enapan bagi beban terma-paksi di dalam kekonsistenan tanah, beban paksi awal, serta beban terma yang berbeza.

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LIST OF ABBREVIATIONS

ASHP	-	Air-Source Heat Pump
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
BSCS	-	British Soil Classification System
GSHP	-	Ground Source Heat Pump
HVAC	-	Heating, Ventilation and Air-Conditioning
IGSHPA	-	International Ground Source Heat Pump Association
LL	-	Liquid Limit
PI	-	Plasticity Index
PL	-	Plastic Limit
MDD	-	Maximum Dry Density
OMC	-	Optimum Moisture Content
SGEP	-	Shallow Geothermal Energy Pile
UCT	-	Unconfined Compression Test
USCS	-	Unified Soil Classification Soil
VDI	-	Verein Deutscher Ingenieure

LIST OF SYMBOLS

ρ_{dmax}	=	Maximum dry density of soil
f_s	=	Ultimate skin friction
α	=	Adhesion factor of cohesive soil
β	=	Drained interface strength parameter
δ'	=	Soil interface friction angle
I_P	=	Plasticity Index
σ'_{v0}	=	In-situ vertical effective stress (effective overburden pressure)
τ_{int}	=	Soil interface shear strength
s_f	=	Settlement at ultimate load
S_u	=	Undrained shear strength
G_s	=	Specific Gravity
w	=	Moisture content
w_L	=	Moisture content at liquid limit
w_P	=	Moisture content at plastic limit

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Malaysia is a tropical country located near the Equator with an average temperature that varies from 20 to 32°C. Since the hot and humid weather is experienced throughout the year, air conditioning systems are used to combat the effect of heat, where it accounts for 16 to 50 percent of the total electricity consumption (Saidur *et al.*, 2007). Typically, office buildings consume about 21% of a country's total commercial energy use (Chirarattananon and Taweekun, 2003). Based on this assumption, it is estimated that total energy used by Malaysian office buildings is about 6090 GWh in year 2007 (Saidur, 2009). Furthermore, in a comprehensive study conducted by Saidur (2009), it was found that air-conditioning systems comprise of one of the main electricity consumers in most of the buildings, consuming around 57% of the electricity in office buildings.

In the near future, it is expected that there will be higher energy usage demands in buildings due to various factors, e.g. a requirement of improved comfort levels, and omore time spent inside buildings. Therefore, energy efficiency in buildings is a prime objective for energy policy at regional, national, and international levels (Lombard *et al.*, 2008). As required in the green building technology initiative nowadays, existing structures can be modified into energy efficient infrastructures by modifying the existing structural elements within a building. A good example of such modification is the shallow geothermal energy pile (SGEP) technology, a newly explored type of sustainable geostructure.

The energy pile system is designed to achieve energy efficient space heating and cooling for residential and commercial buildings of various sizes; while satisfying load bearing requirements of the underlying foundation (Gao *et al.*, 2008). It uses the embedded structural elements e.g. piles in soil as a medium to transfer thermal energy between the building and the soil directly underneath it. Heat exchanger piles transport the ground thermal energy to buildings via heat exchanger fluids that circulate in heat exchanger pipes embedded in the piles (Brandl, 2009).

Nowadays, geothermal energy pile systems have been implemented throughout the world, for example in countries such as Austria, Switzerland, United Kingdom, Japan, China and Hong Kong. However, the engineering community has addressed concerns regarding the effect of thermal loads on the performance of energy piles during its operation. Therefore, there is a need to gain a better understanding of the effect of these thermal loads on the energy pile to justify its use on a large scale, particularly in Malaysia. Recently, the behaviour of the geothermal energy piles under the coupled axial and thermal loads (otherwise known as thermo-mechanical load) has been the subject of research of European and Asian researchers alike. For instance, full-scale in-situ tests on energy pile systems were carried out by Laloui *et al.* (2006). in Switzerland and by Bourne-Webb *et al.* (2009) in United Kingdom.

On the other hand, numerical models of energy pile systems; specifically on soil-structure interaction was developed by Knellwolf *et al.* (2011) and by Ouyang *et al.* (2011) to gain a better understanding of the geothermal energy pile behaviour under operational conditions. More recently, Shin *et al.* (2014) also conducted a numerical study on ground heat exchange system, which pertains to the energy pile research. Regardless, further work is needed to understand the mechanism for soil-pile interaction behaviour at the soil-pile interface, in response to temperature changes (Ouyang *et al.*, 2011; Suryatriyastuti *et al.*, 2012).

Even though geothermal energy pile systems have gained recognition and acceptance in other countries, the technology has not been widely implemented in other countries, including Malaysia. Very little is known about the performance of the geothermal energy pile system in tropical countries, e.g. Malaysia, which will mostly require the system to perform under cooling conditions. Nonetheless, cooling dominated borehole heat exchanger systems are found in Hong Kong (Man *et al.*, 2011) and in Greece (Sagia *et al.*, 2012). However, these researchers mainly focus on the cooling and heating performances of the buildings, with very little emphasis on the performance of the geothermal energy piles under thermo-mechanical loading.

In addition, there are two main concerns with regards to the implementation of geothermal energy pile system. First is the uncertainty about the thermal effects to the soil-structure interaction due to cyclic thermal loads which may affect the long-term structural integrity and durability of the structural foundation (Rosenberg, 2010). Secondly, there is currently no standard design method that considers the complex interactions between thermal storage and the mechanical behaviour of these geostructures (Knellwolf *et al.*, 2011). Therefore, for years, the dimensioning of heat exchanger piles has been based on empirical considerations (Boënnec, 2008). Consequently, the safety factors that are usually employed for conventional pile design are considerably increased.

1.2 Problem Statement

As previously stated, significant studies had been carried out through full-scale experiment tests to examine the effects of both thermal and mechanical loading of energy pile systems. However, the full-scale experimentations are usually expensive and time consuming, and there is a need to develop new techniques to analyse and gain a better understanding of the thermal effects on the soil-structure interaction in the energy pile systems.

The geothermal energy foundation system is an element of “sustainable structure” that has been developed in recent years; hence the published data on long-term performance are scarce. Therefore, experimental investigations on geothermal energy piles are able to provide significant information with regards to their long-term performance. There are only four known laboratory experimental studies conducted to observe the behaviour of these energy piles; where two studies on single gravity energy piles embedded in sand, and two centrifuge study on energy piles in silt have been carried out to date. Accordingly, additional testing and new analyses are required to better understand the mechanisms of thermal soil-structure interaction in energy piles.

1.3 Aim and Objectives of Research

The aim of this research is to establish a preliminary geothermal energy pile testing facility, to produce the load-settlement curves generated by thermo-axial load tests. Since full-scale field testing is considered as an expensive research endeavour, a laboratory physical modelling test with instrumentation approach is taken to achieve this aim. A series of laboratory scale pile loading model tests were conducted in a single-gravity energy pile model testing facility. These pile load tests were conducted under firm and soft soil conditions with a combination of different axial loads, thermal loads and thermo-axial loads. In order to achieve the aim of this research, the following objectives have been identified:

i. To develop a reliable testing approach to characterize the load-settlement behaviour of laboratory scale model energy pile foundations in single gravity conditions.

ii. To evaluate the thermal settlement due to different thermal loads of model pile embedded in soil with different strength values.

iii. To determine the impact of different thermo-axial loads on the bearing capacity of the model pile embedded in soil with different strength values.

1.4 Scope of Work

In order to achieve the objectives of research, the following scope has been determined. First and foremost, this research focuses on the closed-loop ground-source heat pump (GSHP) system. In particular, this study focuses on the model foundation and soil behaviour under varying thermo-axial loads. The materials used in this research includes S300 kaolin (representing the model soil), and stainless steel (close-ended steel tube representing the model energy foundation). Furthermore, the experimental investigations were carried out in the UTM Geotechnical Laboratory.

The material classification was carried out via several tests, using standard methods such as the British Standard and the American Society for Testing and Materials (ASTM). Specifically, the clay material properties are determined via the particle size distribution test, Atterberg Limits test, and specific gravity test for soil classification purposes. Furthermore, soil strength was also carried out, namely the unconfined compression strength test and shear vane test. Two types of reconstituted soft kaolin soil were prepared through compaction to achieve the undrained shear strength of about 25 kPa and 37 kPa.

Then, the small-scale single gravity physical model foundation design was carried out and it consisted of two parts: the soil preparation and model test setup design. For the model soil preparation, both the soil container and loading frame were designed to facilitate the soil sample preparation process. Subsequently, the model test design was carried out where the design of load testing assembly and instrumentation takes place. Next, the setup of the experiment and the pilot tests are carried out. Once the pilot tests are able to confirm the repeatability of the experiment, the main physical modeling test stage commences thereafter.

1.5 Significance of Research

The constantly increasing energy demand, especially for the use of HVAC systems in buildings requires local researchers to look for sustainable energy sources, and a possible answer lies in the use of the geothermal energy pile system. Furthermore, testing the geothermal energy pile system in Malaysia adds another dimension to the energy pile system evaluation process, as this technology is inherently site specific. Different weather, soil profiles and building cooling requirements makes this a unique problem and is therefore essential to the contribution of knowledge to this newly developed field of sustainable technology. Also, this could lead to a better understanding of the limits of extractable energy in a given geothermal energy pile system (Fragaszy *et al.*, 2011). Ultimately, the findings of this research is hoped to justify the funding and subsequent mobilization of a full-scale geothermal energy pile test, first of its kind to be conducted in tropical conditions.

This research is expected to produce a reliable single gravity model test approach of the geothermal energy pile that is expected to retain a degree of similitude with the complex soil-structure interaction during its operational mode. Therefore, to quantify the effect of thermal load on the energy piles, the development of a model energy pile is proposed to study the phenomenon in a controlled environment. This improved understanding can help the development of design methods and identification of suitable factors of safety for energy piles systems. In a broader scope, these results will be useful for GEP system designers to ensure optimal design and operation of energy pile systems.

1.6 Thesis Outline

This thesis comprised of six chapters. As seen in this first chapter, an introduction to shallow geothermal energy foundations was made to expound on the motivation of the study. This is explained by discussing the research problem in terms of the following research philosophies, namely the ‘problem statement’, ‘objectives of study’, ‘scope of study’, and ‘significance of study’.

Chapter 2 of this thesis presents an in-depth review of ground source heat pumps and shallow geothermal energy pile foundations. The review includes an introduction to the components of a ground source heat pump system, and its installation process. Furthermore, the load-transfer analysis of pile foundations is discussed, followed by the discussion of physical modeling of energy pile systems that were conducted in recent years. Based on the current state of knowledge on shallow geothermal energy foundations, the research gap was determined in order to establish the framework of the current research endeavour.

Meanwhile, Chapter 3 presents the research methodology of the study by describing the laboratory work carried out to achieve the aim and objectives set in the first chapter. In particular, the laboratory experiments that were carried out to determine the soil’s physical, thermal and engineering properties based on the British Standard were addressed in detail. Chapter 4 focuses on the laboratory model of the energy pile system and the procedures adopted to carry out the physical modeling. The elements of the physical model were presented via a detailed explanation that included the design of the testing chamber, the axial load and thermal load control system, data measurement and the instrumentation plan adopted for this study.

In Chapter 5, the results of the laboratory testing and physical model tests are presented and discussed in a comprehensive manner. Results from the soil classification and soil engineering properties tests are also presented. The discussion includes several sub-topics such as bearing capacity, pile head settlement, effects of thermal loads and effects of thermo-axial loads. Chapter 6 lists the main conclusions obtained from this study to underscore the contribution of the work done to the existing body of knowledge. In addition, the recommendations for future research work were also specified and discussed.

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