PHYSICAL AND NUMERICAL MODELLING OF BOTTOM ASH COLUMNS INSTALLED IN SOFT SOIL

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To my kind husband who stood beside his wife at every single step of the way,

To my beautiful daughter who was patient for her mother’s targets,

To my beloved father and mother who constantly encouraged

their daughter to her education.

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ABSTRACT

Stone column technique is one of the most widely used ground improvement techniques over the past 50 years. The technique includes the replacement of the soft soil with granular materials in order to increase the bearing capacity and reduce the settlement. This research investigated the role of a group of bottom ash columns in improving the bearing capacity of soft reconstituted kaolin clay. A series of physical modelling test was conducted to study the behaviour of clay reinforced with bottom ash columns under a rigid footing. The influence of important parameters, including area replacement ratio, length of the columns and the geotextile encasement on the performance of reinforced ground was investigated through a total of 13 model tests. Three (3) different area replacement ratios of 13%, 20 % and 26% and two (2) different lengths of 100 mm (floating) and 200 mm (end bearing) of the columns were investigated in this study. In addition, bottom ash columns were installed in two different methods, which was with geotextile encasement and without encasement. In parallel with physical modelling, finite element analyses were performed using Plaxis 3D Foundation software. The results clearly show that the ultimate bearing capacity of kaolin clay was significantly enhanced by the installation of bottom ash columns. This bottom ash has a great potential to be used as a replacement material for stone column in soft soil improvement work. The area replacement ratio was found to be an extremely important parameter controlling the overall performance of the reinforced foundation in the way that increasing the area replacement ratio resulted with up to 30% increase in the ultimate bearing capacity of composite ground. Increasing the length of the column also enhanced the bearing capacity of the reinforced ground of more than 15%. Floating columns were punched into the clay below the column base, but punching behaviour was eliminated by increasing the length of the column to become end bearing which resulted in the improvement of bearing capacity. Encasing the bottom ash columns with geotextile also resulted in an increase of the ultimate bearing capacity significantly from 25% for end bearing and up to 45% for floating columns. Finally, a design chart was established on the parameters affecting the ultimate bearing capacity of soft clay improved with bottom ash columns.

ABSTRAK

Teknik tiang batu adalah salah satu teknik pembaikan tanah yang paling banyak digunakan sejak 50 tahun yang lalu. Teknik tersebut termasuk penggantian tanah lembut dengan bahan-bahan berbutir untuk meningkatkan keupayaan galas dan mengurangkan enapan. Kajian ini menyiasat peranan sekumpulan tiang abu dasar dalam meningkatkan keupayaan galas tanah liat lembut kaolin. Beberapa siri ujian pemodelan fizikal telah dijalankan untuk mengkaji kelakuan tanah liat yang diperkukuh dengan tiang abu dasar di bawah asas tegar. Pengaruh parameter penting termasuk nisbah penggantian luas, panjang tiang dan pembungkusan geotekstil ke atas prestasi tanah yang diperkuatkan dikaji melalui sejumlah 13 ujikaji model. Tiga (3) nisbah penggantian luas iaitu 13%, 20% dan 26% dan dua (2) panjang yang berbeza iaitu 100 mm (terapung) dan 200 mm (galas hujung) untuk tiang telah diselidik di dalam kajian ini. Di samping itu, tiang abu dasar telah ditanam dalam dua kaedah yang berbeza, iaitu dengan pembungkusan geotekstil dan tanpa pembungkusan. Selari dengan penyiasatan secara pemodelan fizikal, analisis unsur terhingga telah dilakukan dengan menggunakan perisian Asas Plaxis 3D. Keputusan jelas menunjukkan bahawa keupayaan galas muktamad tanah liat kaolin telah dipertingkatkan secara ketara dengan pemasangan tiang abu dasar. Abu dasar ini mempunyai potensi yang besar untuk digunakan sebagai bahan pengganti kepada tiang batu dalam kerja-kerja pembaikan tanah liat lembut. Nisbah penggantian luas didapati merupakan parameter yang sangat penting dalam mengawal prestasi keseluruhan tanah yang diperkukuh yang mana dengan meningkatkan nisbah penggantian kawasan telah meningkatkan sehingga 30% keupayaan galas muktamad tanah komposit. Meningkatkan kepanjangan tiang juga telah mempertingkatkan keupayaan galas tanah yang diperkukuh melebihi 15%. Tiang terapung telah menembusi ke dalam tanah liat pada dasar tiang, tetapi tingkah laku penembusan telah dihilangkan dengan peningkatan panjang tiang kepada tiang galas hujung yang menyebabkan kepada peningkatan keupayaan galas. Membungkusan tiang abu dasar dengan geotekstil juga meningkatkan keupayaan galas muktamad dengan berkesan dari 25% bagi galas hujung dan sehingga 45% bagi tiang terapung. Akhir sekali, satu carta reka bentuk telah diwujudkan bagi parameter yang mempengaruhi keupayaan galas muktamad tanah liat lembut yang diperkuatkan dengan tiang abu dasar.

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LIST OF ABBREVIATION

AAS	-	Atomic Absorption Spectroscopy
AASHTO	-	American Association of State Highway and Transportation Officials
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
LL	-	Liquid Limit
PI	-	Plasticity Index
PL	-	Plastic Limit
SL	-	Shrinkage Limit
TWBT	-	Thin Wall Brass Tube
USCS	-	Unified Soil Classification System

LIST OF SYMBOLS

A_c - Area of bottom ash column

A_r - Area replacement ratio

A_s - Area of sample

c - Cohesion

C_C - Coefficient of curvature

C_U - Coefficient uniformity

C_c - Compression index

c_v - Coefficient of consolidation

C_s - Swelling index

c_u - Undrained shear strength

d_c - Diameter of bottom ash column

D_g - Diameter of soil grains

e - Void ratio

G_s - Specific gravity

H_c - Height of bottom ash column

H_s - Height of soil (model ground)

k - Coefficient of permeability

kN - Kilo newton

kPa - Kilo pascal

m - Moisture content

m_v - Coefficient of volume change

Mg - Mega gram

MN - Mega newton

m/s - Metre per second

mm - Milimetre

μm - Micrometre

q - Deviator stress

q_u - Ultimate bearing capacity, ultimate deviator stress
q_{max} - Maximum deviator Stress
w_{opt} - Optimum moisture content
ρ_d - Dry density
ϕ - Internal friction angle
σ_n - Normal pressure
γ_{min} - Minimum unit weight
γ_{max} - Maximum unit weight
γ_{dry} - Dry unit weight
γ_{sat} - Saturated unit weight

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Due to the increasing rate of population and the need for development of the human societies, the utilization of marginal sites and poorer soils became inevitable nowadays. Among the growing methods of ground treatment, stone column technique is considered as an efficient, cost effective and environmental friendly for improving the soft cohesive soils. The technique involves the replacement of 10-35% of the in-situ soil with granular materials compacted in long cylinder holes to improve the strength and consolidation characteristics of soils under light to moderate loaded structures; such as embankments, storage tanks and highways (Killeen, 2012). The rigidity and high stiffness properties of the aggregates improve the bearing capacity and decrease the overall and differential settlement of the in-situ soil. Moreover, the high permeability of the aggregates reduce the consolidation time.

In addition, there is some urgency in the world today to consider sustainable development in construction industry. The unmanageable use of non-renewable natural materials such as gravel, rock, sand, timber, concrete, steel and the waste products from the construction sector, have direct impact on the environment. The utilization of by-products or waste instead of natural material is one of the ways that shall be considered in order to achieve sustainable development.

In Malaysia, the coal-fired power plant plays an important role in the power generation sector, and is the main source of energy. According to Baruya (2010) the coal demand in Malaysia is more than 30 Mtonne/year. The major reason of this high demand of coal is because coal-fired power plant plays an important role in the power generation sector. As shown in Table 1.1, Tanjung Bin, Jimah, Sultan Salahuddin Abdul Aziz Shah and Sultan Azlan Shah are the existing power plants in Peninsular Malaysia. These power plants produce lots of waste and surpluses of by-product material as they generate electricity from the burning of coal.

Table 1.1: List of coal-fired plants in Peninsular Malaysia (after Hasan, 2013)

Power Plant	Capacity (MW)	Type	State
Tanjung Bin	2100	Thermal (3 ST)	Johor
Jimah	1400	Thermal (2 ST)	Negeri Sembilan
Sultan Salahuddin Abdul Aziz Shah	2420	Thermal (6 ST)	Selangor
Sultan Azlan Shah	2295	Thermal (3 ST)	Perak

Coal ashes are the waste materials produced during the coal burning in coal-fired thermal power plants (Singh and Siddique, 2013). The coal waste products that produced from coal fired power plants mostly consist of fly ash, bottom ash and boiler slag (Feuerborn, 2005). The lighter particles that are collected form electrostatic precipitators is called fly ash which forms 75% of coal ash produced, while bottom ash is made by agglomeration of the large ash particles that are too heavy to be carried by the flue gases thus drop in the ash hopper at the bottom of the furnace. Bottom ash that forms up to 25% of the total produced coal ashes, generally consist of merged coarser ash particles, which are porous and look like volcanic lava.

The properties of bottom ash make it useful for a variety of construction applications. Bottom ash particles are physically coarse, porous, glassy, granular and grayish in color. Travedi and Singh (2004) reported the coefficient of permeability of bottom ash up to 9.6×10^{-4} m/s, which revealed that the bottom ash showed medium degree of permeability. According to Goutam and Ventappa, (2008), the maximum unit weight of bottom ash by compaction ranging from 11.87 kN/m^3 to 18 kN/m^3 with optimum moisture content ranging from 12 % to 34 %.

Large production of bottom ash from coal burning in Malaysia has resulted in waste issues and since it has similar properties with granular aggregates, with particle size ranging from fine sand to fine gravel, which is between 0.1 mm to 10 mm (Kumar and Stewart, 2003a; Marto *et al*., 2010), it has the potential to be used as substitute material in stone column. This technique allows the reduction in the project cost and resolve the disposal problem of the bottom ash products. Wood *et al*. (2000) mentioned two advantages of stone columns' installation in soft clay. Firstly, the stiffer properties of granular materials and their higher frictional strength in comparison with clay particles, lead the columns to act as pile and through shaft resistance and end bearing, transfer the load to a greater depth. Secondly, the granular material possess higher permeability than clay particles and by shortening the drainage path, cause the increase in the consolidation rate and improve the strength.

Several design criteria affect the stone column behaviour, for instance the column's stiffness, the area replacement ratio, A_r, (ratio of area of the column, A_c, to area of soil, A_s), column spacing (s) and height penetrating ratio H_r, (ratio of height of the column, H_c, to height of soil, H_s). Previous work by Hu (1995) on bearing capacity of group of stone columns revealed that the load bearing performance of column inside a group is not similar to single isolated column proposed by Hughes and Withers (1974). He also proposed that area replacement ratio is a very important parameter that control the overall operation of stone column reinforced foundation and high value of area replacement ratio (over 25%) significantly increase the bearing capacity of improved ground. Moreover, Hu (1995) suggested that generally the increase in the column length give rise to the overall stiffness of the reinforced ground.

In a very soft soils with low undrained shear strength, the encased stone columns could be applied for better performance. The concept of encasing stone columns with geotextile traced back to the study conducted by Van Impe and De

Beer (1983). Utilizing the geosynthetic material as confinement around the stone column would prevent extra bulging, ground contamination with granular aggregate and excessive settlement. Moreover, geosynthetic encasement assist the increase in the shear strength of the nearby soil and bearing capacity of the composite ground (Murugesan and Rajagopal, 2006; Malarvizhi and Ilamparuthi, 2007).

1.2 Problem Statement

Low bearing capacity and high compressibility are among the features of problematic soils such as soft clay deposit, marine clay and peat. Vertical granular columns (generally known as stone columns) is the ideal ground improvement technique for lightly loaded and flexible structures. However, for a very soft clay the formation of stone column might be problematic because of lateral spread of aggregates. In such cases, encasing the stone column with suitable geosynthetic could be an ideal solution that help in better performance of stone columns. Several researchers conducted studies on the performance of stone columns (Ali *et al.*, 2014; Kumar, 2013; Gniel and Bouazza, 2009; Murugesan, 2009; McCabe, 2007; Malarvizhi and Ilamparuthi, 2004; McKelvey, 2004; Wood, 2000; Hu, 1995, Hughes and Wither, 1974) but few have tried the use of bottom ash as substitute materials in stone columns (Marto *et al.,* 2013). Moreover, none has evaluated the improvement in the bearing capacity of soft soil reinforced by geotextile encased bottom ash columns. Utilization of alternative materials for stone columns is essential while the conventional column’s aggregates were from natural non-renewable materials. Furthermore, the bottom ash production has resulted in disposal and environmental problems, in which the need for storage spaces rises the expenses for acquiring large areas. Subsequently the utilization of bottom ash in geotechnical engineering work could help in the reduction of project costs (Hasan, 2013). This is because the bottom ash can be obtained for free or bought in minimal price compared to the non-renewable natural materials.

Besides the experimental investigation, numerical simulation is beneficial, by which it is possible to check several parameters affecting the behaviour of bottom ash columns. Simulating the columns numerically facilitates in performing the parametric study and helps in considering different parameters affecting the behaviour of bottom ash column simultaneously.

1.3 Aim and Objectives

This study aimed to determine the improvement made by the installation of bottom ash column in soft clay. This is achieved through the following objectives:

i. To quantify the improvement of bearing capacity achieved by installing small groups of bottom ash columns through 1g physical modelling tests.
ii. To determine the influence of area replacement ratio, column length and geotextile-encasement on the bearing capacity of small groups of bottom ash columns.
iii. To predict the ultimate bearing capacity of small groups of bottom ash columns through numerical simulation.
iv. To produce preliminary design charts on the use of bottom ash columns as soil improvement method.

1.4 Scope and Limitation of the Research

This research investigated the performance of soft kaolin reinforced with small groups of bottom ash columns under a rigid footing with the aid of small-scale laboratory physical model test and numerical simulation. A total of thirteen bearing capacity tests on rigid footing were conducted. One test was performed on the kaolin clay without any reinforcement as a control test, while the rests were in two groups of either clay reinforced with uncased bottom ash columns or with geotextile encased columns.

The bottom ash, which was collected from Tanjung Bin Power Plant in Pontian, Johor was used as the granular material (63 µm to 2.36 mm particle size) in vertical column, while the 'S300' white kaolin powder used as ground model in this study was bought from Kaolin (M) Sdn. Bhd., based in Selangor, Malaysia. Polyfelt TS20 with 10 kN/m tensile strength and 115 mm/s permeability was sewn to form a cylindrical shape and used as the geotextile encasement for the bottom ash columns.

The basic tests in accordance to British Standard (BS) and/or the American Society of Testing Material (ASTM) were performed on both the bottom ash and kaolin in order to determine their physical and mechanical characteristics. The tests performed on bottom ash included the dry sieve test, specific gravity test, relative density test, constant head permeability test and standard compaction test. While for kaolin, the physical and mechanical properties were determined through hydrometer test, Atterberg Limit test, specific gravity test, falling head permeability test, vane shear test and one dimensional consolidation test.

The commercial 3D finite element software called "Plaxis 3-D Foundation" Version 2 was used in numerical simulation to evaluate and compare the results obtained from experimental model tests. Soft soil creep and Mohr-Coulomb model were used in simulating the model ground and bottom ash columns, respectively.

1.5 Significance of the Research

In recent years, the engineering community has proposed many alternative methods to improve soft soils. These methods should be sustainable. Accordingly, the stone column technique became more popular nowadays. In order to retain non-renewable natural material in balance there is an urgent need for an alternative method to substitute natural material with waste or by-products. The aim of this study, which was the determination of the improvement made by the installation of bottom ash columns in soft soil was in line with proposing a ground improvement technique that preserve sustainability. The significance of this study includes the followings:

i. This study offers the uncased and geotextile encased bottom ash columns as ground improvement technique to improve soft clay. The method is practical in improving the bearing capacity of clay and by reuse of bottom ash instead of stone in stone columns can help in recycling this coal by-product and therefore supports the environmental consideration besides being cost effective and economic.
ii. The performed research considered the effects of geotextile encasement and bottom ash columns arrangement and dimension on improvement of the bearing capacity of soft clay. Thus, the results of the study provided better understanding of the performance of uncased and geotextile encased bottom ash columns as ground improvement technique, which can later be applied in the field.
iii. The preliminary design charts offered by this research could be used as a design tool for the determination of the bearing capacity of soft clay, particularly that correspond to the 10 kPa undrained shear strength of the soil.

1.6 Hypothesis

Utilization of uncased and geotextile encased bottom ash columns in group is expected to enhance the bearing capacity of kaolin clay. In particular, the following hypotheses are expected.

i. The area replacement ratio, A_r, has great effect on the performance of bottom ash columns in which the increase in A_r is expected to increase the bearing capacity of the composite ground.
ii. Increasing the column length from floating to end bearing condition would enhance the bearing capacity of the composite ground.
iii. The utilization of the geotextile by encapsulating the bottom ash column is expected to improve a better bearing capacity results as compared to the uncased bottom ash column composite ground.

iv. Results of the ultimate bearing capacity of small groups of bottom ash columns through numerical simulation are estimated to be in line with the experimental results.

1.7 Thesis Structure

This thesis consists of six chapters. The essence of each chapter is as follows:

Chapter 1 defines the background of problems and also affirms the aim and the objectives, scopes and limitations, and the significance of the study.

Chapter 2 provides brief background information of stone column foundations and reviews previous research works relevant to the subject of the present study. Most existing theories and approaches similar to this research in design practice were reviewed.

Chapter 3 describes the research methodology that included the design and manufacturing of testing apparatus and experimental equipment used in the laboratory physical model study. Details on the specimen preparation and general procedures used for the model testing and the construction of bottom ash columns are also discussed.

In the Chapter 4, the results from the physical modelling tests are presented and discussed. The discussion covers several issues such as bearing capacity of clay reinforced with group of columns through physical modelling. The failure mechanism for bottom ash columns reinforced foundation under a rigid footing load is presented based on information deduced from the deformed shapes of columns after tests. The properties of research materials used in this research that includes the basic properties and classification of kaolin and bottom ash along with supplementary tests are also presented.

Chapter 5 discusses and summarises the results obtained from numerical simulation tests and compares with experimental results.

Finally, the conclusion and the contributions of this study as well as the recommendations for future research are described in Chapter 6.

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