PERFORMANCE OF SOFT GROUND IMPROVED BY FLOATING BOTTOM ASH COLUMNS

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DEDICATION

Especially dedicated to the soul of my father, ***Abuelgasim Abdelrhman*** who has always given me indefinite love, trust, constant motivation throughout my life.

To my lovely mother, ***Fatima Hussein,*** for her patience, endless love, prayers, and endurance of ups and downs while completing this thesis

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To my brothers and all my friends, for their help and loyalty

This thesis is dedicated to them

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ABSTRACT

The stone column approach has been utilized over the past 60 years to stabilise the soft ground by partially replacing the compressible soil with more stable materials such as aggregate and sand. In practice, the granular material with a diameter of 20 mm to 75 mm is used as column filler material. In this research, the bottom ash material was used as a substitute material in the granular columns instead of the natural aggregate. A series of small-scale 1g physical modelling tests were carried out to investigate the behaviour of soft clay after being treated with a group of bottom ash columns beneath a rigid footing. A parametric study was performed to examine the effect of key design parameters such as; area replacement ratio and height penetration ratio on the bearing capacity and settlement characteristics. Whereas, a total of 19 physical model tests were conducted. A set of strain-controlled loading tests were performed to determine the ultimate bearing capacity, while a dead load method was adopted to examine the settlement characteristics. The physical modelling tests were carried out on the untreated and treated ground with bottom ash columns. Three area replacement ratios of 13 %, 20 %, and 26 % and three-column height of 50 mm, 100 mm, and 150 mm were adopted. The deformation and failure mechanism of the ground model was observed through capturing images during the loading test. Then, the Particle Image Velocimetry technique (PIV), GeoPIV: MATLAB software was used to analyse the collected images. The results clearly proved that the bearing capacity of the soft ground improves significantly with the incorporating of the bottom ash columns. Moreover, a higher area replacement ratio with longer columns demonstrated better load capacity enhancement. Also, it was found that the magnitude of total settlement reduced as the area replacement ratio increased. In addition, the total settlement of the reinforced ground showed a decreasing trend with the increase of the column height. In parallel to the physical modelling tests, three-dimensional numerical analysis was conducted via Plaxis 3D foundation software. This method was adopted to validate the experimental outcomes, since it is more economical and takes less time to complete in comparison to the full-scale model. Two different types of constitutive models were used to simulate the soft ground and bottom ash columns namely; the Soft Soil model and Mohr-Coulomb model. Comparisons between the results obtained from the physical model test and numerical simulation were made considering the different area replacement ratios and column height penetration ratios. The finite element analysis results were used to verify the experimental findings and a good agreement was found between the two methods since the difference is less than 20 % and is considered acceptable. The results revealed that the area replacement ratio and column height penetration ratio significantly influenced the overall performance of the treated ground. Whereas, the stiffness, load-bearing capacity, and settlement characteristics of the reinforced ground improved by increasing the area replacement ratio and column height penetration ratio; a 172 % enhancement in bearing capacity was attained with 26 % area replacement ratio and 0.75 column penetration ratio. A similar observation was obtained for LECA- treated ground under a constant rate of loading. The relationships between ultimate bearing capacity and area replacement ratio or column height to diameter ratio were plotted. From the relationships, six proposed design equations were developed for practical use to estimate the ultimate bearing capacity of the reinforced ground under a rigid footing. Another six design equations were also established to predict the normalised bearing capacity factor using the same parameters (area replacement ratio or column height to diameter ratio). Furthermore, the rationality of the proposed design equations was successfully verified using the finite element results.

ABSTRAK

Pendekatan tiang batu telah digunakan sejak 60 tahun yang lalu untuk menstabilkan tanah lembut dengan menggantikan sebahagian tanah boleh mampat dengan bahan yang lebih stabil seperti agregat dan pasir. Dalam praktik, bahan berbutir dengan diameter 20 mm hingga 75 mm digunakan sebagai bahan pengisi lajur. Dalam penyelidikan ini, bahan abu mendap digunakan sebagai bahan pengganti dalam tiang butiran dan bukannya agregat asli. Satu siri ujian pemodelan fizikal 1g berskala kecil telah dijalankan untuk menyiasat kelakuan tanah liat lembut selepas dirawat dengan sekumpulan tiang abu mendap di bawah tapak tegar. Kajian parametrik telah dilakukan untuk mengkaji kesan parameter rekabentuk utama seperti; nisbah penggantian luas dan nisbah penembusan ketinggian pada kapasiti galas dan ciri-ciri penanaman. Manakala, sebanyak 19 ujian model fizikal telah dijalankan. Satu set ujian pembebanan terikan-terkawal telah dilakukan untuk menentukan kapasiti galas muktamad, manakala kaedah beban mati digunapakai untuk memeriksa ciri-ciri penanaman. Ujian pemodelan fizikal telah dijalankan di atas tanah yang tidak dirawat dan dirawat dengan tiang abu mendap. Tiga nisbah penggantian luas 13 %, 20 %, dan 26 % dan ketinggian tiga lajur 50 mm, 100 mm dan 150 mm telah diterimapakai. Mekanisme ubahbentuk dan kegagalan model tanah diperhatikan dengan menangkap imej semasa ujian pembebanan. Kemudian, perisian Velocimetry Imej Zarah, Teknik PIV, GeoPIV: MATLAB digunakan untuk menganalisis imej yang terkumpul. Hasilnya jelas terbukti bahawa kapasiti galas tanah lembut meningkat dengan ketara apabila digabungkan tiang abu mendap. Selain itu, nisbah penggantian luas yang lebih tinggi dengan lajur yang lebih panjang menunjukkan peningkatan kapasiti beban yang lebih baik. Juga, didapati bahawa magnitud jumlah penanaman berkurangan apabila nisbah penggantian luas meningkat. Di samping itu, jumlah penanaman tanah bertetulang menunjukkan corak menurun dengan peningkatan ketinggian lajur. Selari dengan ujian pemodelan fizikal, analisis berangka tiga dimensi telah dijalankan menggunakan perisian tapak 3D Plaxis. Kaedah ini digunapakai untuk mengesahkan hasil eksperimen, kerana ia lebih menjimatkan dan mengambil masa yang lebih sedikit untuk disiapkan berbanding dengan model skala penuh. Dua jenis model konstitutif yang berbeza digunakan untuk mensimulasikan tiang tanah lembut dan abu mendap iaitu; model tanah lembut dan Mohr-Coulomb. Perbandingan antara keputusan yang diperoleh daripada ujian model fizikal dan simulasi berangka telah dibuat dengan mengambil kira nisbah penggantian luas dan ketinggian lajur yang berbeza. Keputusan analisis unsur terhingga digunakan untuk mengesahkan dapatan eksperimen dan persetujuan yang baik didapati antara kedua-dua kaedah memandangkan perbezaannya kurang daripada 20 % dan dianggap boleh diterima. Keputusan menunjukkan bahawa nisbah penggantian luas dan nisbah penembusan ketinggian tiang mempengaruhi prestasi keseluruhan tanah yang dirawat secara signifikan. Manakala, kekakuan, kapasiti galas beban, dan ciri-ciri penanaman tanah bertetulang bertambah baik dengan meningkatkan nisbah penggantian luas dan nisbah penembusan ketinggian tiang. peningkatan sebanyak 172% dalam kapasiti galas telah dicapai dengan nisbah penggantian kawasan 26% dan nisbah penembusan tiang 0.75. Pemerhatian yang sama diperolehi untuk tanah yang dirawat LECA di bawah kadar pemuatan yang tetap. Hubungan antara kapasiti galas muktamad dan nisbah penggantian luas atau nisbah ketinggian lajur kepada diameter telah diplotkan. Daripada perhubungan, enam persamaan rekabentuk yang dicadangkan telah dibangunkan untuk kegunaan praktikal untuk menganggarkan kapasiti galas muktamad tanah bertetulang di bawah tapak tegar. Enam lagi persamaan rekabentuk juga telah diwujudkan untuk meramalkan faktor kapasiti galas ternormal menggunakan parameter yang sama (nisbah penggantian luas atau nisbah ketinggian lajur kepada diameter). Tambahan pula, rasional persamaan rekabentuk yang dicadangkan telah berjaya disahkan menggunakan keputusan unsur terhingga.

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LIST OF ABBREVIATIONS

ACAA	-	American Coal Ash Association
BS	-	British Standards
ASTM	-	American Society of Testing Material
XRD	-	X-Ray Diffraction
SEM	-	Scanning Electron Microscopy
OMC	-	Optimum Moisture Content
MDD	-	Maximum Dry Density
BCR	-	Bearing Capacity Ratio
PIV	-	Particle Image Velocimetry
LVDT	-	Direct Displacement Measurement
EP	-	Extraction Procedure Toxicity Test
SLS	-	Serviceability Limit State
SSM	-	Soft Soil Model
USCS	-	Unified Soil Classification System
LL	-	Liquid Limit
PL	-	Liquid Limit
PI	-	Plasticity Index
CU	-	Consolidated Undrained Triaxial Test
UCT	-	Uniaxial Compression Test
USCS	-	Unified Soil Classification System
TCLP	-	Toxicity Characteristics Leaching Procedure
ULS	-	Ultimate Limit State
MC	-	Mohr-Coulomb
IF	-	Bearing Capacity Improvement Factor
IC	-	Increase in ultimate bearing capacity
AAS	-	Atomic Absorption Spectroscopy

LIST OF SYMBOLS

α	-	Area Replacement Ratio
β	-	Column height penetration ratio
A_c	-	Column area
A_s	-	Area of the sample
A	-	Total area
H, L	-	Column height
H_s	-	Height of sample
S_c	-	Column spacing
D, D_c	-	Column diameter
D_e	-	Equivalent diameter
D_g	-	Gradation of granular material
γ	-	Unit weight
c	-	Cohesion of soil
φ	-	Friction angle
q_u	-	Ultimate carrying capacity
D_f	-	Foundation depth
B	-	Foundation width
N_s	-	Number of stone columns
ν	-	Poisson's ratio
K_{ac}	-	Coefficient of active earth pressure,
K_0	-	Coefficient of lateral earth pressure at rest
I	-	Second moment of inertia
R^2	-	Coefficient of correlation
η	-	Settlement reduction factor
SRR	-	Settlement reduction ratio
S_u	-	Settlement of the unreinforced soil
S_r	-	Settlement of the unreinforced soil
ψ	-	Dilatancy angle
c'	-	Effective cohesion
φ'	-	Effective friction angle

N_c, N_q, N_γ	-	Bearing capacity factor
q	-	Surcharge pressure
W	-	Weight
σ_c	-	Stress in the stone column
σ_s	-	Stress in the soil
$\lambda*$	-	Modified compression index
κ *	-	Modified swelling index
E	-	Young Modulus
c_s	-	Swelling index
c_c	-	Compression index
e	-	Void ratio
k	-	Permeability
G_s	-	Specific gravity
σ	-	Stress
P	-	Point load
mm	-	Millimetres
cm	-	Centimetres
m	-	Meter
Pa	-	Pascal
N	-	Newton

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Construction on soft soil deposits poses a significant challenge in the field of geotechnical engineering. Due to the low shear strength and high compressibility of soft soil, numerous engineering issues in the form of; bearing capacity failure, slope instability, or excessive settlement might occur during or, in most cases, after the construction phase.

Ground improvement method is the best option to improve the inadequate characteristics of soft soil. Although the ground improvement techniques can enhance the characteristics of the soft soil, not all techniques are economical, suitable, and preferable. Out of the several techniques, granular column is one of the most preferred, cost-effective, and widely used in construction. Stone column is a technique that uses granular materials such as crushed rock, gravel, and sand as supplements in the soft soil. Alternative materials are required to prevent the consumption of natural resources and promote sustainable development. One of the best alternatives involves the use of recycled waste materials.

The generation of electricity in coal-fired thermal power plants annually generates a large quantity of ashes which are categorised as waste materials (Singh and Siddique, 2013). The coal waste products that are generated from coal-fired power plants mainly comprise of fly ash, bottom ash, and boiler slag (Feuerborn, 2005). According to Muhardi et al. (2010), the huge amount of coal ash has become a great concern to the power plants companies given the increase in demand for ash storage areas. Since the disposal costs are rising, this might result in significant social and environmental problems.

Kumar & Stewart (2003) proved that the characteristics of bottom ash material are very similar to those of natural sand. Thus, there is a good potential of using bottom ash as a replacement material to sand in granular columns. By introducing bottom ash columns, the construction cost of projects can be considerably decreased meanwhile the need for a discharge area for bottom ash can be significantly reduced.

1.2 Problem Statement

Construction on soft soil deposits requires ground modification or improvement to enhance its mechanical characteristics. Granular column is a technique that involves replacing a part of the soil with granular material such as sand, gravel, or crushed rocks. It is constructed in soft cohesive soil because it can enhance the bearing capacity, decrease the settlement, and speed up the dissipation of pore water pressure. In order to prevent the uncontrollable usage of natural materials, there is an urgent need for substitute materials such as waste or other by-products.

In general, two important criteria are governing the design of the foundation; allowable bearing capacity and tolerable settlement. The design of granular columns in soft clays is usually governed by settlement characteristics rather than the bearing capacity to support the applied loads. Granular columns have been used to support structures and embankments, especially when the settlement or differential settlement is involved because of their higher strength and stiffness compared to the soft soil. Furthermore, it has the ability to sustain a larger portion of the applied load, which enhances the performance of foundation ground. Hence, by using the bottom ash as a replacement for the granular material in the stone column application, the construction costs can be considerably decreased while the strength of soft clay can be further improved on treatment with bottom ash columns.

Many studies have been conducted to investigate the performance of granular columns in soft clay. However, few have attempted to study the utilisation of bottom ash as a substitute material. Most of the researches that were conducted on the bearing capacity of the treated soil with bottom ash columns either used the end bearing or floating type (Moradi et al., 2018, 2019). Hasan et al., (2011, 2014) performed laboratory model tests to investigate the improvement of the shear strength of soft kaolin clay after treatment with single and group of bottom ash columns. In a parametric study, Marto et al., (2014) similarly examined the influence of different parameters regarding the consolidation and shear strength characteristics of soft clay after being treated with single and group of bottom ash columns.

The influence of geosynthetic bottom ash columns on the shear strength of soft clay was observed by Hasan et al., (2016), the parametric study was carried out in a small-scale laboratory test on a single column and group of bottom ash columns encased with polyester non-woven geotextile material. The effect of the encasement length was studied and a comparison between a single column and a group of columns was made. The study revealed that the encasement of the bottom ash column significantly enhanced the overall shear strength of the soft clay and that the improvement was dependent on the column diameter and height. Recent attempts at utilising a series of physical modelling tests to determine the bearing capacity and failure mechanism of floating and end-bearing encased bottom ash columns installed in a soft ground have been conducted by (Moradi et al., 2018, 2019). The study was adopted to examine the effect of area replacement ratio and geosynthetic encasement.

The limited laboratory investigations that have been reported in the literature were mainly concerning shear strength and bearing capacity. However, there are no published data in the literature on settlement characteristics of bottom ash columns in soft clay. In many cases, it is more likely that settlement under operating conditions is more critical than bearing capacity. In order to understand the effect of installing a group of floating bottom ash columns in soft clay under a rigid footing, an experimental investigation could be performed. Since there are lots of parameters that influence the behaviour of bottom ash columns and the time-consuming nature of evaluating all of them using experimental investigation, simulating the columns numerically can be beneficial. Also, this will facilitate execution of the parametric study and be helpful when considering various parameters affecting the behaviour of the bottom ash column simultaneously.

1.3 Aim and Objectives

This research aims to examine the performance of soft kaolin clay treated with a small group of floating bottom ash columns beneath a rigid footing. A series of small-scale laboratory models will be performed to study the effect of area replacement ratio (ratio of the column area, $A_{c,}$ to the area of the sample, A_s) and height penetration ratio (ratio of the column height, H, to the height of sample, H_s) of a group of floating bottom ash columns on the bearing capacity and settlement characteristics of soft clay after treatment with bottom ash columns. Moreover, the ground deformation and column failure mode will observe using PIV technology. The results from experimental tests will be validated using the numerical simulation with PLAXIS 3D software. In order to attain the aim of this study, the specific objectives are as follows:

(a) To determine the enhancement of bearing capacity attained by installing a small group of floating bottom ash columns using experimental modelling.

(b) To measure the settlement under the design load of the soft ground reinforced with a group of floating bottom ash columns.

(c) To compare the physical model tests results of the bearing capacity and settlement with finite element analysis.

(d) To develop a preliminary design equation to estimate the ultimate bearing capacity of reinforced ground with a small group of floating bottom ash columns using experimental modelling and validate it with numerical simulation.

1.4 Scope and Limitation of Study

This research is aimed at examining the role of a small group of floating bottom ash columns in enhancing the bearing capacity and settlement characteristics of soft clay beneath a rigid footing through physical and numerical modelling. Two main materials were used for the preparation of the physical model. Commercial kaolin clay powder (L2B20) was used for preparing the soft ground model, whereas, bottom ash obtained from Tanjung bin power plant, Johor was utilized as granular material.

The physical and mechanical characteristics of kaolin and bottom ash were performed based on British Standards (BS) and the American Society of Testing Material (ASTM). The tests that were conducted on kaolin include; Atterberg limit test, sieve analysis test, specific gravity test, standard compaction test, falling head permeability test, one-dimensional consolidation test, and vane shear test. On the other hand, the laboratory testing that was performed on bottom ash, includes sieve analysis test, specific gravity test, relative density test, standard compaction test, direct shear box test, consolidated undrained triaxial test, and constant head permeability test. The microstructure of the bottom ash was studied through X-ray diffraction (XRD) and X-ray energy dispersive spectrometry (EDS) while the leaching characteristics were examined with atomic absorption spectroscopy (AAS) and inductively coupled plasma optical emission spectroscopy (ICP-OES).

The physical modelling tests were carried out in a small rigid testing chamber of dimension, 400 mm×150 mm×430 mm. The kaolin sample was consolidated to a depth of 200 mm to obtain undrained shear strength of about 7.5 kPa. The experimental testing was conducted on the untreated (clay bed only) and improved ground model with bottom ash columns under a rigid footing of size 100 mm width and 150 mm long. The bottom ash columns were installed in three different depths of 50 mm, 100 mm, and 150 mm. Three area replacement ratios of 13 %, 20 %, and 26 % were adopted; referring to four, six, and eight columns respectively and corresponding to 25 mm column diameter.

For numerical simulation, Plaxis 3D Foundation was used to compare and validate the results achieved from the physical model tests. The two constitutive models that were used to simulate the ground model and bottom ash columns are Soft Soil and the Mohr-Coulomb models.

1.5 Significance of Research

In recent decades, a variety of geotechnical construction methods have been developed to improve the performance of soft soil. Ground improvement with stone columns is one of the popular methods for supporting footings and embankments constructed on soft soil. Stone column is considered an effective technique for decreasing the settlement and increasing the time-rate of consolidation of soft clay soil. In most cases, end-bearing columns are typically used for the design. However, due to the construction costs and machine depth limitations, floating columns are occasionally used. Since bottom ash, a by-product of coal-burning, has proven properties similar to sand soil, there is a possibility of it being used as sand replacement in stone column applications. To avoid the consumption of gradually depleting natural materials, the use of recycling material from the waste of coal, such as bottom ash, is an excellent solution. Therefore, by utilizing bottom ash as granular material in granular columns and floating columns instead of end bearing columns, the construction cost can be reduced while ensuring sustainable development

This research studies the behaviour of small groups of floating bottom ash columns in soft kaolin clay using physical and finite element modelling (PLAXIS 3D). The laboratory experiments and numerical results provide a further understanding of the improvement of the soft ground treated with floating bottom ash columns using varying area replacement and column height penetration ratios. In addition, it promotes the development of appropriate analytical methods. The importance of this research is that it will set guidelines for the design of floating bottom ash columns in soft kaolin clay. Although Moradi et al., (2019) had studied the bearing capacity of soft clay treated with floating bottom ash columns, there is a lack of information on the important parameters such as the effect of height penetration ratio.

1.6 Thesis Outlines

This thesis is organized into six chapters and each chapter consists of the following information:

Chapter 1 outlines the research background, problem statement, objectives of the research, the scope, limitation, and the significance of the study.

Chapter 2 presents the review of the available literature from the previous researches relating to the study. The review includes a brief description of the stone column ground improvement method; principle, materials, construction, design considerations, and applications. In addition, the basic concept for the estimation of the load-bearing capacity, settlement prediction, and failure mechanism are also highlighted. This chapter also presents the numerical finite element modelling related to the theme of the research which includes; materials description and constitutive modelling. This chapter also covers the characteristics of bottom ash material and its application in construction. In addition, previous studies on similar work such as; physical modelling, numerical simulation PLAXIS 3D are also addressed. Furthermore, past researches on Lightweight Expanded Clay Aggregate (LECA) columns are highlighted and a comparison with bottom ash columns is also presented.

Chapter 3 explains the materials used in the preparation of the ground model, the collection of testing material, experimental equipment, and the detailed testing procedure used in the laboratory testing. The laboratory equipment used to prepare the physical modelling which includes sample preparation tools, column installation, pressure system, and loading devices are also presented. Additionally, the calibration of the instrumentation, setting of physical modelling, and supplementary tests are discussed. The procedure for observing the ground deformation through the Particle Image Velocimetry technique is also highlighted. This chapter also explains the methodology used in numerical modelling which includes model geometry, selection of suitable constitutive model, boundary conditions, loading stages, mesh generation, and material properties.

Chapter 4 contains the obtained results from the laboratory tests and the physical modelling experiments. The laboratory tests results include the physical and mechanical properties of kaolin and bottom ash. The chemical and leaching characteristics of bottom ash are also presented. The discussion of the physical modelling results including the analysis of the supplementary tests, PIV test and column deformation mechanism are also presented in this chapter. The physical modelling and PIV test results cover the bearing capacity and settlement aspects. A comparison between the obtained results with LECA material is also discussed.

Chapter 5 presents the findings from the finite element analysis using PLAXIS 3D software. The discussion of the results is divided into four main parts. The first part is carried out to obtain the ultimate bearing capacity of the untreated and treated ground model. The second part focuses on determining the settlement of the ground model under the design load. Comparison with the obtained results from the physical model is also made. The third part elaborates the development of the design guidelines based on the results obtained from physical and numerical modelling. The last part validates the proposed design equations with the LECA material.

Finally, Chapter 6 summarises the main conclusions from the findings of this research as well as suggestions and recommendations for future researches.

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