LOAD CARRYING CAPACITY OF COLUMNS SUPPORTED EMBANKMENT ON SOFT SOIL USING TREATED BOTTOM ASH

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DEDICATION

This thesis work is dedicated to my parents, who have always supported, encouraged, and loved me unconditionally and whose continuous advice have motivated me to work hard. Also, to my siblings and family members who always been there for me.

This work is especially dedicated to my brothers for their continuous support and encouragement during difficulties in life.

This thesis is dedicated to all my friends for their help.

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ABSTRACT

When an embankment is to be built on ground that is too weak and compressible to support the embankment appropriately, columns of firm material can be installed in the soft ground to offer essential support by carrying the embankment load to a stiff stratum. This procedure is referred to as column supported embankments. There are two main motives to employ columns supported embankments: a) expedite construction compared to traditional construction techniques such as staged construction or pre-designed vertical drains, b) protection of nearby amenities against distress, like settlement of existing carriageways when a highway is being extended. Despite its extensive usage in the construction industry, the current situation of technology suggests that further investigation is needed to give a deeper understanding of the technology in reference to sustainable material used in column, performance and failure mechanisms of the columns underneath the embankment. In this study, the performance of a group of bottom ash, cement bottom ash and geopolymer columns in enhancing the load-carrying capacity of soft soil under embankment were investigated. A series of laboratory physical model test was carried out to examine the behaviour of improved ground under an embankment subjected to constant strain loading. The influence of key parameters such as column materials, length of columns and area replacement ratio on the performance of improved ground was investigated by the overall number of 13 model tests. The research variables include two column lengths of 150 mm (floating) and 200 mm (end bearing), three area replacement ratios of 11%, 16% and 22%, three column materials such as bottom ash (stone column), cement bottom ash and geopolymer (rigid column). In addition, numerical analysis was carried out in parallel to model the behaviour of laboratory model tests by using Plaxis 3D foundation software. It is evident from the results that the load-carrying capacity of the foundation soil under embankment increased significantly with columns installation. The load-carrying capacity of bottom ash columns reinforced clay with the area replacement ratio of 11%, 16% and 22% increased by 24.31%, 39.09% and 63.35% for the floating columns and 27.49%, 42.63% and 83.60% for the end bearing columns as compared to the unreinforced model. Cement bottom ash columns reinforced clay with an area replacement ratio of 16% and 22% increased the load-carrying capacity by 19.53% and 69.39% for the floating case and 53.00% and 78.24% for the end bearing columns in comparison to unreinforced test. While geopolymer columns reinforced ground with an area replacement ratio of 16% increased the load-carrying capacity by 64.47% and 83.48% for the floating and end bearing columns, respectively. The results showed that the area replacement ratio and column length significantly affect the performance of reinforced ground. The load-carrying capacity and stiffness of foundation soil under embankment enhanced by increasing the area replacement ratio and column length. In addition, bottom ash columns reinforced ground showed perfectly plastic behaviour failure, while cement and geopolymer columns reinforced ground under embankment possess ductile behaviour failure. Bulging as a mode of failure occurred in the bottom ash columns, while tilting and punching occurred in the cement bottom ash and geopolymer columns. The stress concentration ratio was greater than unity for column reinforced models. Furthermore, the experimental and numerical results showed good agreement. The stress-settlement curves achieved from both experimental and numerical models followed the same pattern. Preliminary design charts were produced from the relationship between load-carrying capacity and area replacement ratios for different length to diameter ratios of bottom ash, cement bottom ash and geopolymer columns. The design charts will help the construction industry in designing bottom ash, cement bottom ash and geopolymer columns.

ABSTRAK

Apabila tambakan hendak dibina di atas tanah yang terlalu lemah dan mudah termampat untuk menyokong tambakan dengan baik, tiang daripada bahan yang keras boleh dipasang dalam tanah lembut untuk memberikan sokongan sepatutnya dengan memindahkan beban tambakan ke stratum yang sangat keras. Prosedur ini disebut sebagai tambakan yang disokong tiang/lajur. Terdapat dua tujuan utama untuk menggunakan tambakan yang disokong tiang: a) pembinaan yang dipercepat berbanding dengan teknik pembinaan tradisional seperti pembinaan berperingkat atau untuk pra-ujikaji aliran menegak, b) perlindungan kemudahan berdekatan daripada kecemasan, seperti mendakan pada jalan raya sedia ada apabila membuat penambahan lebuhraya. Walaupun penggunaannya yang meluas dalam industri pembinaan, keadaan teknologi saat ini menunjukkan bahawa penyelidikan lebih lanjut diperlukan untuk memberikan pemahaman yang lebih mendalam mengenai teknologi tersebut dengan merujuk pada bahan lestari yang digunakan dalam tiang/lajur, prestasi dan mekanisme kegagalan lajur di bawah tambakan. Dalam kajian ini, prestasi sekumpulan tiang/lajur abu dasar, simen-abu dasar dan tiang geopolimer dalam meningkatkan daya galas tanah lembut di bawah tambakan telah diselidik. Satu siri ujian model fizikal makmal telah dilakukan untuk memeriksa kelakuan tanah komposit di bawah tambakan yang dikenakan beban secara regangan seragam. Pengaruh parameter utama seperti bahan lajur, panjang lajur dan nisbah penggantian kawasan terhadap prestasi penambahbaikan tanah disiasat dengan jumlah keseluruhan 13 model ujian. Pemboleh ubah kajian merangkumi dua panjang tiang iaitu 150 mm (terapung) dan 200 mm (kedalaman penuh), tiga nisbah penggantian kawasan iaitu 11%, 16% dan 22%, tiga bahan tiang abu dasar (lajur batu), simen–abu dasar dan geopolimer (tiang tegar). Di samping itu, analisis berangka dilakukan selari dengan ujian model makmal dengan menggunakan perisian Plaxis 3D. Ini terbukti dari hasil kajian bahawa daya galas tanah komposit di bawah tambakan meningkat dengan ketara dengan pemasangan tiang. Kapasiti beban bagi tiang abu dasar sebagai pengukuhan tanah clay terhadap nisbah penggantian kawasan 11%, 16% dan 22% meningkat sehingga 24.31%, 39.09% dan 63.35% untuk tiang terapung dan juga 27.49%, 42.63% and 83.60% untuk tiang penuh seperti yang dibandingkan dengan tanah yang tiada pengukuhan. Bagi tiang simen-abu dasar dengan nisbah penggantian kawasan 16% dan 22% meningkatkan kapasiti tanggungan beban sehingga 19.53% dan 69.39% untuk tiang terapung, dan 53.00% dan 78.24% untuk tiang penuh seperti yang dibandingkan dengan tanah tiada pengukuhan. Manakala untuk tiang geopolymer dengan nisbah penggantian kawasan sebanyak 16% meningkatkan kapasiti tanggungan beban, masing-masing sebanyak 64.47% dan 83.48% untuk tiang terapung dan tiang penuh. Hasil kajian menunjukkan bahawa nisbah penggantian kawasan dan kedalaman penembusan tiang mempunyai pengaruh terhadap prestasi pengukuhan tanah. Kapasiti tanggungan beban dan kekukuhan asas tanah di bawah tambakan dapat dipertingkatkan dengan penambahan nisbah penggantian luas dan panjang tiang. Tambahan lagi, pengukuhan tanah tiang abu dasar menunjukkan kegagalan kelakuan plastik dengan sempurna, sementara pengukuhan dengan tiang simen dan geopolimer di bawah tambakan mempunyai kegagalan kelakuan mulur. Pembonjolan adalah mod kegagalan yang berlaku di tiang/lajur abu dasar, manakala kecondongan dan penembusan tiang/lajur diperhatikan untuk tiang abu dasar dan tiang geopolimer. Nisbah tumpuan tekanan adalah lebih besar untuk model pengukuhan tiang. Di samping keputusan eksperimen dan numerik yang menunjukkan keselarian yang baik. Lengkung tekanan – mendakan juga tercapai daripada kedua-dua model eksperimen dan numerik juga menunjukkan bentuk yang sama. Carta rekabentuk asal dihasilkan daripada hubungan di antara kapasiti tanggungan beban dan nisbah penggantian kawasan bagi nisbah panjang kepada diameter abu dasar yang berbeza, simen-abu dasar dan tiang geopolimer.Carta rekabentuk tersebut akan membantu industri pembinaan dalam rekabentuk abu dasar, simen-abu dasar dan tiang geopolimer.

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LIST OF ABBREVIATIONS

ACAA	-	American Coal Ash Society
Ar	-	Area Replacement Ratio
ASTM	-	American Society for Testing and Materials
BC	-	Bottom ash Column
BS	-	British Standard
CBA	-	Coarser Bottom Ash
CSE	-	Columns Supported Embankment
CSR	-	Column Stress Ratio
EB	-	Embedded beam
EDX	-	Energy Dispersive X-ray
FBA	-	Fine-size Bottom Ash
GC	-	Geopolymer Column
GESC	-	Geosynthetic Encased Stone Columns
LEM	-	Linear Elastic Model
LVDT	-	Linear Variable Pressure Transducer
MBA	-	Medium-size Bottom Ash
MCM	-	Mohr-Coulomb Model
OMC	-	Optimum Moisture Content
PVC	-	Polyvinyl Chloride
PPT	-	Pore Pressure Transducer
RC	-	Rigid Columns
SC	-	Stone Column
SEM	-	Scanning Electron Microscopy
SPT	-	Soil Pressure Transducer
SRR	-	Stress Reduction Ratio
SSM	-	Soft Soil Model
UTM	-	Universiti Teknologi Malaysia
XRD	-	X-Ray Diffraction

LIST OF SYMBOLS

A_{col}	-	Area of Columns
A_r	-	Area Replacement Ratio
A_s	-	Area of Surrounding Soil
A_T	-	Total Territory Area
c_c	-	Coefficient of Curvature
c_u	-	Undrained Shear Strength of Soil
D	-	Diameter of Column
D_{eq}	-	Equivalent Diameter of Columns
E	-	Modulus of Elasticity
e_1	-	Initial Void Ratio
e_f	-	Final Void Ratio
G_s	-	Specific Gravity
H_f	-	Final Height
k	-	Permeability
kN	-	Kilo Newton
kPa	-	Kilo Pascal
L	-	Length of Column
m_1	-	Initial Moisture Content
mm	-	Millimetre
m/s	-	Metre per Second
µm	-	Micrometre
NaOH	-	Sodium Hydroxide
Na_2SiO_3	-	Sodium Silicate
S	-	Spacing between Columns
σ	-	Stresses Acting on the Embankment Surface
σ_{col}	-	Stresses Acting on the Column
σ_s	-	Stresses Acting on the Surrounding Soil
q_s/cu	-	Bearing Ratio
δ/w	-	Settlement Ratio
ν	-	Poisson Ratio
ϕ	-	Internal Friction Angle
γ_d	-	Dry Unit Weight

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the twentieth century, advances in the industrial revolution have led to an increase in socio-economic growth setting up new employment opportunities and successive scientific development in a short time frame. As a result, the entail for infrastructural development in large-scale projects like airport, dams, and harbours etc. and small range projects like railways, dwellings and roads have been extensively increased on inadequate soil. This scenario has driven the construction to be carried out on soft ground and marshy sites due to the unavailability of adequate soil.

Soft ground possesses higher compressibility and insufficient undrained shear strength (lower than 25 kPa) like silt, loose sand, peat and clay deposits (Flodin and Broms, 1981; Rashid, 2011). Soft soils have anisotropic behaviour by virtue of their accumulation history. The properties of soil in conjunction with conditions like variations in stress history and pore pressure distributions depend on the clay particles orientation during the deposition stage. Clay consists of intermittently organized particles assembled to make an anisotropic structure. The interaction between the particles destroys gradually as a result of an increase in plastic strain due to loading (Rouainia and Muir Wood, 2000). Besides this, clays possess a viscous behaviour approach to persisting deformation.

When highways pass through a low-lying ground, then embankments have to be constructed to carry the roadways toward serviceable elevation. These embankments may encounter stability issues and will provoke settlement for a long duration if built on extremely compressible soft clays. In recent years, the demand for constructing such embankments increased rapidly due to the expansion of the traffic network. However, the prevention of embankment failure and controlling subsoil deformation within the permissible limit is challenging job for geotechnical engineers.

Column supported embankments (CSE) are usually built on soft soil to enhance the stability of embankment, expedite construction, limit the differential and residual settlements, and provide protection to the nearby amenities (Filz *et al.*, 2012; Smith, 2005; Stewart and Filz, 2005). The column supported embankments have proven as an effective solution compared to the conventional geotechnical methods for construction over soft soil (Collin *et al.*, 2005; Han, 2015). The columnar supports within the soft ground are classified as flexible columns (among which are lime columns and stone columns), semi-rigid columns (e.g; construction of soil-cement and lime cement columns employing grouting or deep mixing method) and rigid pile (such as vibro-concrete piles, steel piles, timber piles and concrete piles) (Smith, 2005). The columns should be properly designed and supposed to be stronger and rigid than the available ground, which may impede the supported embankment's excessive settlement. The column supported embankment would be a suitable engineering solution if protection of adjoining existing amenities or rapid construction is essential. CSE is mostly adopted in the United Kingdom, Japan, Malaysia, Poland, Scandinavia and also getting more attention in other countries. CSE method has great applicability at various soft ground location, comprising coastal sites where new embankments have to be constructed or widening of existing embankments are needed.

Nowadays the recycled industrial by-products drawing attention as construction material (Hansson, 2008). The uncontrolled usage of natural materials like; sand, gravel, rock, steel, concrete, timber, and residual products generated from industrial operations directly influence environmental sustainability. The utilization of recycled materials like pulverized fly ash, bottom ash, shredded waste tyres and steel slag instead of natural materials is one of the possible solutions to achieve long term development in ground stabilization (Zukri and Nazir, 2018).

In Malaysia, coal is a major source for electricity generation in coal-fired power plants, and coal consumption follows a 9.7% raise each year (Jamaludin, 2009). Baruya (2010) stated that the coal requirement is greater than 30 million tonnes per year (Mt/y) in Malaysia. The fuel demand for electricity production in Peninsular Malaysia is shown in Figure 1.1 from PMESILO-2017 (Peninsular Malaysia Electricity Supply Industry Outlook 2017). It is evident from the comparison of various sources for fuel consumption, coal is a vital resource for power generation.

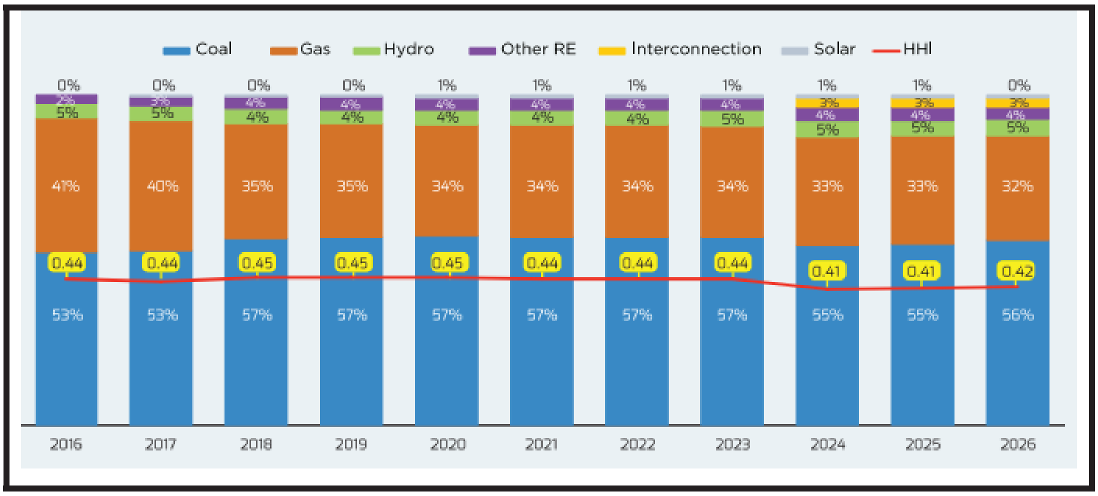

Figure 1.1 Fuel consumption for power generation in Peninsular Malaysia (Peninsular Malaysia Electricity Supply Industry Outlook 2017)

As stated in the PMESILO-2017, that the utilisation of gas is expected to be reduced by approximately 12% and coal would be used as an alternative due to low price and easily manageable as compared to the other fuel sources (Jamaludin, 2009). Table 1.1 describes the coal consumption for power generation at various electricity units. The growing demand for electricity generation resulted in a huge amount of surpluses and waste by-products, which are discarded as a landfill and causes a threat to environmental sustainability (Ramzi *et al.*, 2016).

Table 1.1 Coal demand for different coal-burnt power plants from 2014 to 2016 in million tonnes per year (PMESILO, 2017)

Year	**2014**	**2015**	**2016**
Tanjung Bin	4.9	6.5	7.6
Jimah	3.2	4.1	4.3
Manjung	7.1	10.4	9.6
Kapar	3.5	3.7	4.1
Total (Mt/y)	18.7	24.6	25.4

The raw product of coal burning in coal-operated thermal power stations contains coal ashes (Singh and Siddique, 2013). The coal by-product generated during the combustion of coal in the coal-fired units mostly composed of bottom ash, fly ash and boiler ash (Feuerborn, 2005). Fly ash consists of lighter particles accumulated from the Cotrell precipitator and contributes 75-80% to the total mass of coal ash. While bottom ash (BA) comprised of heavy and large coal particles which are assembled in a hopper at the lower section of the furnace. BA generally composed of porous coarser ash particle and makes 20-25% of the overall generated coal ashes (Maliki *et al.*, 2017; Mukhtar *et al.*, 2003; Singh and Siddique, 2013). Although in developed countries, a certain portion of these coal ashes is effectively recycled, but still large proportion of coal ashes are directly disposed of as a landfill in the developing countries, as the disposal cost has been less than the utilization cost (Kim and Lee, 2015). However, the deposition of coal ashes has recently become a complex issue due to several reasons. The cost of dumping is increasing due to the insufficient capacity of existing ash ponds, which resulted in the construction of new sites far from the power stations and increasing the threat to environmental sustainability (Jang, 2010). In response to these challenges, many researchers have focused on techniques to optimize the application of coal ashes with the aims to decrease their dumping and rehabilitation.

In general, most researchers have concentrated on the utilization of fly ash and concluded that fly ash possesses appropriate properties for usage in different construction fields. Conversely, limited studies are reported on the application of bottom ash as a construction material. Bottom ash possesses higher permeability and low density (Kim and Lee, 2015), higher shear strength and lower compressibility

(Lynn *et al.*, 2017; Maliki *et al.*, 2017). BA indicated a resemblance of properties to that of granular aggregate particles (Kumar and Stewart, 2003; Marto *et al.*, 2010). BA is frequently used aggregate as a substitute for gravel and sand (ACAA, 2014). Other major usage includes, as an ingredient in concrete and mortar due to its coarser particles and alternative for natural soils and gravel in geotechnical engineering fills and embankments. According to the American Coal Ash Association (2006) report on bottom ash utilization, more than 45% of all bottom ash generated is mostly utilized in transportation and geotechnical applications such as road base material and structural fills. Figure 1.2 show the general applications of bottom ash in the United States.

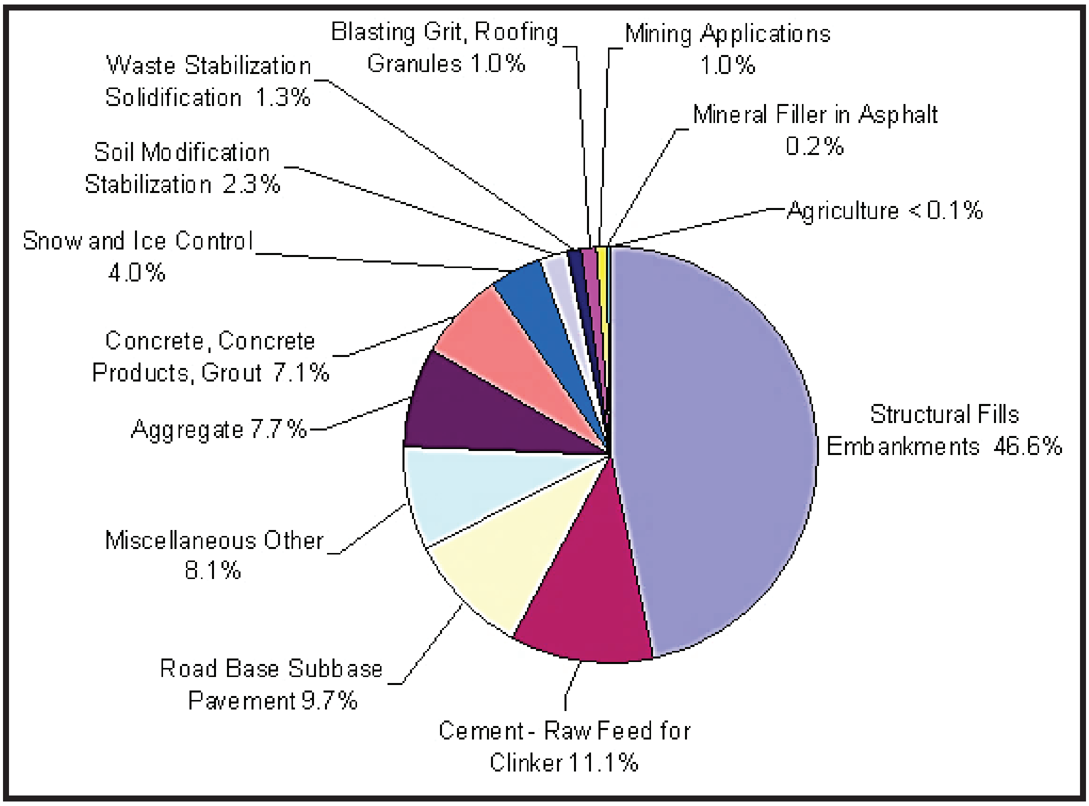

Figure 1.2 Application of bottom ash in the United States as a percentage of entire re-used (ACAA, 2006)

Due to irregular particle shape and higher permeability, BA can be used as a geotechnical drainage material (Kim and Lee, 2015). Lee (2008) and Kim (2009) conducted a study on the usage of bottom ash as a vertical sand drainage material and horizontal sand mat respectively. According to the findings achieved from both studies, BA is considered a suitable material for drainage purposes, given the fact that consolidation time decreased with the application of BA in comparison to the usual sand drain. Lee *et al.* (2010) concluded that bottom ash piles have offered better drainage capacity and more clogging resistance as compared to the ordinary aggregate piles. In ordinary aggregate piles, silt and clay particles from the surrounding soil penetrate the voids of crushed gravel piles and tend to reduce the drainage capacity. In addition to these characteristics, BA is widely used as a mineral addition and artificial aggregate in cementitious composites (Toraldo *et al.*, 2013). Previous studies suggested that utilization of bottom ash in concrete/mortar proved good pozzolanic reactivity, increased compressive strength and heat of hydration (Kim, 2015; Kim *et al.*, 2014).

1.2 Problem Statement

The construction of new roadway embankments on the soft ground with low undrained shear strength is increasing due to the rapid evolution of the traffic system. Embankments construction on soft soil is an extremely challenging job for geotechnical engineers due to excessive settlement and probable bearing failure of embankment and foundation soil. Over the last few decades, embankments failure over soft soils created substantial uncertainty in stability analysis. When embankment over soft soil is subjected to repeated heavy traffic loads, then deformation will occur in the embankment by chasing the foundation soil movement. The consequence impacts of soil movement are settlement, sliding due to insufficient shear strength and embankment failures. However, various techniques are adopted to mitigate the settlement and increase the load-carrying capacity. One method is to establish columnar supports in the foundation soil such as stone columns, rigid columns etc.

Most of the studies have been performed on the performance of stone columns under the embankment loading, but each of them focused on the natural stone aggregates or primary aggregate (Das and Deb, 2018; Serridge and Synac, 2007; Xu *et al.*, 2021; Yoo, 2010). However, growing awareness for sustainable development in ground improvement is leading to a larger desire to utilize recycled aggregates and secondary aggregates (industrial by-products) (Jefferson *et al.*, 2010; Serridge, 2005). Bottom ash is an industrial by-product generated in power stations for electricity production. Since the acceptance of bottom ash usage rises in the developed countries, these markets have the possibility to reuse all the bottom ash generated annually. Bottom ash possesses good drainage capacity and resistance to clogging (Lee *et al.*, 2010; Lee, 2008), and has proven good pozzolanic reactivity and increase in compressive strength of mortar/concrete (Kim *et al.*, 2014; Kim and Lee, 2015). As a part of attaining environmental sustainability in ground improvement, there is a growing desire to utilize the bottom ash in stone column technique. Several researchers have successfully applied uncased and geotextile encased bottom ash columns for reinforcing soft soil under rigid footing to increase the bearing capacity and reduce the settlement (Marto *et al.*, 2016; Moradi *et al.*, 2019; Moradi *et al.*, 2018). The geotextile encasement is provided to increase the tensile strength of the columns but is still weak in compression when installed in soil with low undrained shear strength. Therefore, rigid columns are installed in weak soil to increase the bearing capacity due to their higher rigidity. Therefore, a comprehensive understanding is needed to investigate the behaviour of soft foundation soil reinforced with a group of bottom ash columns (stone column) and cement bottom ash and geopolymer columns (rigid column) under the embankment. The utilization of bottom ash as columns material under embankment will help to solve the dumping issue, reduce the project cost, and will bring sustainability in ground improvement.

In addition to experimental study, numerical analyses must be carried out concurrently to model the stress-settlement behaviour of columns supported embankments by considering the influencing factor such as area replacement ratios and Column length. Thus, numerical simulation of the physical model facilitates in carrying out the parametric study to understand the actual behaviour of embankment resting on columns reinforced soil.

1.3 Aim and Objectives

The aim of this research is to investigate the load-carrying capacity performance of bottom ash, cement-bottom ash and geopolymer columns reinforced foundation soil under embankment subjected to constant strain loading. A series of instrumented small-scale laboratory model tests will be carried out on the columns reinforced soil under embankment loading. This research will focus on the following objectives to be achieved.

(a) To examine the properties of untreated and treated bottom ash by carrying out a series of laboratory tests.

(b) To quantify the load-carrying capacity improvement of soft foundation soil reinforced with bottom ash, cement bottom ash and geopolymer columns under embankment subjected to constant strain loading.

(c) To evaluate the effect of governing factors such as area replacement ratios and column length on the performance of reinforced ground subjected to constant strain loading.

(d) To predict the load-carrying capacity of treated and untreated bottom ash columns supported embankment on soft soil through numerical simulations.

(e) To produce preliminary design charts on the usage of bottom ash, cement bottom ash and geopolymer columns as soil improvement methods to support embankment using numerical simulations.

1.4 Scope of the Study

This research was carried out to examine the performance of soft foundation soil improved with a group of bottom ash, cement bottom ash and geopolymer columns (floating and end bearing columns) under the embankment subjected to constant strain loading. This study was carried out using three approaches; (a) basic properties tests were performed for kaolin, residual soil, bottom ash, cement bottom ash and geopolymer, (b) instrumented small-sized laboratory physical model was carried out to investigate the behaviour of treated and untreated bottom ash columns supported embankment, (c) 3D modelling was performed to simulate the behaviour of treated and untreated bottom ash columns reinforced soil underneath embankment.

The bottom ash was obtained from the Tanjung Bin power plant located at Pontian, Johor. The size of the granular material used in the bottom ash, cement bottom ash columns was less than 2 mm. The brown kaolin powder was obtained from the Kaolin (M) Sdn Bhd in Selangor, Malaysia. The residual soil for the embankment was collected from a site inside Universiti Teknologi Malaysia, Johor Bahru.

To determine the mechanical and physical properties of bottom ash and kaolin clay, various tests were performed following the specifications of the American Society of Testing and Material (ASTM) and British Standard (BS). A series of tests including a specific gravity test, laser scattering particle size test, relative density test, standard compaction test and constant head permeability test was conducted on the bottom ash. While, laser scattering particle size test, falling head permeability test, vane shear test, Atterberg limit test, and one-dimensional consolidation test were performed for kaolin. In addition, the residual soil was subjected to laser scattering particle size test, specific gravity, plasticity limits and compaction test.

Instrumented small-sized laboratory physical model was carried out to investigate the behaviour of treated and untreated bottom ash columns supported embankment. The brown kaolin slurry was used to represent the soft ground model and inserted into the rectangular experimental chamber. The embankment was prepared from the residual soil passed through a 2 mm sieve. A gradient of 1:2 (vertical: horizontal) was provided to the embankment slope. The experimental model test for unreinforced kaolin under embankment was selected as a benchmark model. The remaining tests were divided into three groups, such as clay reinforced with bottom ash columns, cement bottom ash columns and geopolymer columns. Two columns length of 150 mm (floating columns) and 200 mm (end bearing columns) and three area replacement ratios of 11%, 16% and 22% were selected to improve the foundation soil. For area improvement ratio 11%, 16% and 22%, the number of columns were 12, 16 and 24, respectively.

The finite element based commercial software program “Plaxis 3D Foundation” was employed to model the behaviour of treated and untreated bottom ash columns supported embankment on soft soil and stress-settlement results obtained from the experimental and numerical models were compared.

1.5 Significance of Research

In recent decades, the engineering society has suggested various substitute methods to strengthen soft soils. These techniques need to be more practical, cost-effective, easy to accomplish and time-saving. In order to preserve non-recurring natural material in equilibrium, the construction industry sought an alternative approach to replace the primary aggregate with recycled or secondary aggregates. The goal of this study was to examine the load-carrying capacity of embankment rested on soft ground reinforced with bottom ash, cement bottom ash and geopolymer columns. The utilization of industrial by-product bottom ash in ground stabilization will also help to maintain environmental sustainability. The emphasis of this study considers the followings:

(a) This study proposed the bottom ash, cement bottom ash and geopolymer columns as soil stabilization methods to improve the foundation of soft soil under the embankment. This technique is practical in enhancing the load-carrying capacity of soft ground. The re-use of bottom ash in place of stone aggregate in stone columns and cement bottom ash and geopolymer columns in rigid columns can assist in recycling the coal waste product. The utilization of bottom ash contributes to environmental sustainability despite being available in large proportion and economical.

(b) Furthermore, the study provides an enhanced understanding of the reinforced foundation subjected to embankment loading by changing the area replacement ratio and columns length (End bearing and floating columns). The parametric investigation of this research can offer improved knowledge to engineers and researchers regarding the effect of significant variables on the stress settlement behaviour and load-carrying capacity of columns supported embankment.

(c) The 3D modelling adopted in this research could be applied as a design tool for the construction of embankment over soft soil.

This study has focused on the substitution of bottom ash as a natural stone aggregate in stone columns to strengthen the soft ground under the embankment. Cement bottom ash and geopolymer were used as an alternative material to conventional mortar in rigid columns. This research has multiple contributions in the field of sustainable ground improvement in terms of economy and sustainability. As a sustainable ground improvement, this study investigated the factors influencing the performance of stone columns and rigid columns. Furthermore, bottom ash, cement bottom ash and geopolymer provided a new method for enhancing the load-carrying capacity of soft soil underneath embankment. Preliminary design charts were developed to help the construction industry in designing bottom, cement bottom ash and geopolymer columns under the embankment. This research will help to resolve the dumping or landfill issue of coal bottom ash by utilizing the bottom ash as a substitute for natural aggregates such as natural stone aggregate and sand, which will be a good step toward sustainability. The research relates the economic challenges of a project through which the cost of construction could be reduced due to the usage of industrial by-products in the columns.

1.6 Thesis Overview

This thesis addressed the behaviour of embankment over unreinforced clay and columns reinforced clay and divided it into seven chapters. The description of each chapter is outlined below.

Chapter 1 provides an introduction and background to the columns supported embankment technology. This chapter also consists of a problem statement, aim and objective, scope, and significance of the research.

Chapter 2 consist review of the literature regarding ground improvement methods, stone columns, rigid columns, and related work to the columns supported embankment. In chapter 2 some aspects related to stone columns and rigid columns are presented which including introduction, installation methods and their suitability. Besides this, introduction to column supported embankment method, feasibility assessment, case histories and some terms like stress concentration ratio, stress reduction ratio and column stress ratio are addressed. This chapter also discuss the bottom ash properties and its application as column material.

Chapter 3 explained the methodology adopted to carry out this research. This chapter briefly discussed the materials testing and equipment used in physical modelling. Details on the equipment calibration, specimen preparation, overall procedure for physical model tests and numerical modelling details are explained in chapter 3.

Chapter 4 discussed the basic properties test results for the materials used in this research, which involves basic properties test of kaolin, residual soil, bottom ash together with other supplementary tests. Unconfined compressive strength, morphological and micrographs results for cement bottom ash and geopolymer are also explained in chapter 4. The unreinforced embankment model results are also discussed in this chapter.

Chapter 5 present the result and discussion of the physical model tests. In this chapter, the stress-settlement relationship, the ultimate load-carrying capacity of clay reinforced with columns group, failure pattern of columns under embankment loading, stress at surrounding soil, stress at column top and bottom, stress concentration ratio and effect of area replacement ratio and column penetration are briefly discussed.

Chapter 6 include the output of numerical modelling. In chapter 6, numerical modelling results and comparison of experimental and numerical results are explained and summarized.

Finally, the key conclusions obtained from the findings of this research as well as suggestions and recommendations for future work are provided in chapter 7.

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