SOFT CLAY STABILISATION USING LIGHTWEIGHT AGGREGATE FOR RAFT AND COLUMN MATRICES

AZHANI ZUKRI

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Faculty of Engineering
Universiti Teknologi Malaysia

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ABSTRACT

The stone column technique has been used as a soft ground stabilisation method over the past 30 years by using partial replacement of the compressible soil with a more competent granular material such as stone aggregate and sand. The column filler material in current practice normally consist of stone aggregates of 20 mm to 75 mm in diameter. It is compacted into a vertical hole generally of 0.6 meter to 1.0 meter diameters and depths of more than 6 time diameter. The major part of this research is to present the behaviour of stone column group beneath large loaded area through three-dimensional finite element (FE) analysis. Instead of normal aggregate for stone columns, Lightweight Expanded Clay Aggregate (LECA) has the potential to be used as replacement material. By using PLAXIS 3D, LECA columns-raft were modelled as Mohr-Coulomb material and the nonlinear behaviour of soft soil is modelled with Hardening Soil constitutive model. To permit timely analysis in this research and to simulate long term settlement behaviour, drained analysis was adopted to allow for a greater number of sensitivity and parametric analysis to be performed. Parametric study was performed to evaluate the effect of LECA raft thickness (H_r), depth ratio (β), and area replacement ratio (α) on the settlement performance. The obtained results proved that increasing the thickness of replaced soft clay with compacted LECA layer evidently decreases the settlement, where the performance of settlement improvement up to 40%, 60% and 80% for 1.5 m, 2.5 m and 3.5 m depth of LECA replacement, respectively. The settlement ratio of LECA column was found to be reduced as the column length increases until end bearing condition, where the highest settlement ratio of 4 for α = 0.4 can be achieved. Higher area replacement ratio results in a higher settlement ratio, which indicating that closer spacing provide better improvement. In addition, the replacement of LECA raft on LECA column (LECA columns-raft) significantly decreases the settlement of the soft ground. For higher α with longer columns and thicker rafts provide better settlement improvement. However, LECA columns-raft performance chart can be referred for economic design. Meanwhile, the bearing capacity of LECA raft was found to be increased with increasing of raft thickness. The research indicates that the most controlling parameter in the prediction of LECA columns-raft bearing capacity (q_u) is the area replacement ratio, where q_u increases considerably with increase of α. The physical modelling was established in laboratory with 1:20 scaling factor to validate numerical analysis. The method can provide even more accurate verification, economical and require less time to perform compare to field testing and full-scale model. The results from physical modelling agree well with numerical prediction where the difference is less than 20% and is considered acceptable. The dimensionless relationship between settlement ratio (S/S_{uc}) against β was plotted for every α and H_r. Five design charts are proposed for practical engineer to predict the settlement of LECA columns-raft and LECA columns under large loaded area. Two design charts are also developed for LECA raft settlement prediction. It can be referred to as early estimation of settlement ratio according to the thickness of replacement. The reliability of design charts is successfully validated using PLAXIS 3D.

ABSTRAK

Teknik tiang batu telah digunakan sebagai kaedah penstabilan tanah lembut sejak 30 tahun yang lalu dengan menggunakan penggantian separa tanah lembut dengan bahan yang lebih kompeten seperti agregat batu dan pasir. Bahan pengisi tiang batu yang digunakan pada masa kini biasanya terdiri daripada agregat batu bergaris pusat 20 mm hingga 75 mm. Ia dipadatkan ke dalam lubang menegak bergaris pusat 0.6 meter hingga 1.0 meter dengan kedalaman melebihi 6 kali garis pusat lajur. Bahagian utama penyelidikan ini adalah untuk memperlihatkan tingkah laku sekumpulan tiang batu di bawah tindakan beban yang luas melalui analisis unsur terhingga tiga dimensi (FE). Selain daripada agregat biasa, Agregat Tanah Liat Ringan (LECA) berpotensi untuk digunakan sebagai bahan pengganti dalam tiang batu. Dengan menggunakan perisian komersil 3D PLAXIS, tiang-rakit LECA dimodelkan sebagai bahan 'Mohr-Coulomb' manakala kelakuan tidak linear tanah lembut dimodelkan dengan model 'Hardening Soil'. Untuk membenarkan analisis disiapkan tepat pada masanya dan bagi mensimulasikan tingkah laku mampatan jangka panjang, analisis tersalir digunakan untuk membolehkan lebih banyak analisis parametrik dilakukan. Kajian parametrik telah dilakukan untuk menilai kesan ketebalan rakit LECA (H_r), nisbah kedalaman (β), dan nisbah penggantian kawasan (α) kepada prestasi pemampatan. Hasil yang diperoleh jelas membuktikan bahawa dengan peningkatan ketebalan tanah liat yang diganti dengan lapisan LECA yang padat dapat mengurangkan mampatan, di mana prestasi penambahbaikan mencapai sehingga masing-masing 40%, 60% dan 80% untuk ketebalan 1.5 m, 2.5 m dan 3.5 m penggantian LECA. Nisbah mampatan tiang LECA pula didapati berkurangan dengan peningkatan panjang lajur sehingga mencapai keadaan galas akhir dimana nisbah mampatan tertinggi yang dicapai adalah 4 bagi α=0.4. Nisbah penggantian kawasan yang lebih tinggi menghasilkan nisbah mampatan yang lebih tinggi, menunjukkan bahawa jarak dekat antara tiang LECA memberi peningkatan nisbah mampatan yang lebih baik. Di samping itu, didapati tiang-rakit LECA dapat mengurangkan mampatan tanah lembut dengan lebih ketara. Bagi α yang lebih tinggi dengan tiang LECA yang lebih dalam serta rakit yang lebih tebal memberikan peningkatan mampatan yang lebih baik. Sementara itu, kapasiti tekanan galas rakit LECA meningkat dengan peningkatan ketebalan rakit. Kajian ini menunjukkan bahawa parameter nisbah penggantian kawasan lebih mempengaruhi kapasiti tekanan galas (q_u) tiang-rakit LECA, di mana q_u meningkat dengan peningkatan α. Pemodelan fizikal telah dibina di makmal dengan faktor skala 1:20 untuk mengesahkan analisis berangka. Kaedah ini boleh memberikan pengesahan yang lebih tepat, menjimatkan dan memerlukan hanya sedikit masa untuk dilaksanakan berbanding dengan ujian dilapangan dan pemodelan dengan skala penuh. Nilai pemendapan yang direkodkan dalam pemodelan fizikal hampir sama dengan nilai daripada analisis berangka di mana perbezaannya kurang daripada 20% dan dianggap boleh diterima. Hubungan tak berdimensi antara nisbah penyelesaian (S/S_{uc}) terhadap β telah diplot bagi setiap α dan H_r. Lima carta rekabentuk dicadangkan bagi kegunaan jurutera untuk meramalkan nilai mendapan tiang-rakit LECA dan tiang LECA di bawah beban luas. Dua carta reka bentuk juga dibangunkan bagi meramalkan nilai mendapan rakit LECA sebagai rujukan awal memilih nisbah penyelesaian mengikut ketebalan penggantian. Kebolehpercayaan carta rekabentuk berjaya disahkan menggunakan PLAXIS 3D.

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LIST OF ABBREVIATIONS

LECA	-	Lightweight Expanded Clay Aggregate
3D	-	Three Dimensional
1D	-	One Dimensional
FEM	-	Finite Element Method
FE	-	Finite Element
UU	-	Unconsolidated Undrained
CU	-	Consolidated Undrained
CD	-	Consolidated Drained
LL	-	Liquid Limit
PIV	-	Particle Image Velocimetry
OCR	-	Over consolidation ratio
MC	-	Mohr Coulomb Model
HSM	-	Hardening Soil Model
BL	-	Lateral bulging
BV	-	Vertical bulging

LIST OF SYMBOLS

A, A_r, A_F	-	Area Improvement Ratio
L_c, L, L	-	Length of column
H_s	-	Depth of Soft Soil
H_r	-	Raft thickness
D, D	-	LECA column diameter
s	-	LECA column spacing
B	-	Width of footing
γ	-	Unit weight
S_r	-	Settlement of LECA raft
S_{cr}	-	Settlement of LECA columns-raft
c_u	-	Undrained shear strength
S_N	-	Suitability Number
S/S_{uc}	-	Settlement ratio
S_{uc}	-	Settlement of end bearing column group
S	-	Settlement of floating column group
P, q	-	Load intensity
K_0	-	Lateral earth pressure
ϕ_c	-	Friction angle of column
β	-	Depth Ratio
η	-	Settlement efficiency ratio
n	-	Stress concentration ratio
d_c	-	Diameter of stone column
γ	-	Unit weight of surrounding soil
E_c	-	Column stiffness
E_s	-	Soil stiffness
ν	-	Poisson ratio
L_c	-	Column length
q_u, q_{ult}	-	Ultimate bearing capacity

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CHAPTER 1

INTRODUCTION

1.1 Background

Most coastal zones in the world, such as Japan, Eastern Canada, Norway, Sweden and other Scandinavian countries, India and Southeast Asian countries lie on soft soil deposits. In Malaysia, soft soil layers are found throughout the country and mostly in coastal areas. Many earlier establishments lay spread in the coastal zone area, for examples Kuala Lumpur, Port Klang, Malacca, Johor Bahru and Penang. In fact, all major towns in Malaysia, and all the 14 state capitals, lie in the coastal zone area. Due to its benefits and resources, even with its restricted areas and reserves, coastal region is vulnerable to various threats such as overutilization or unsustainable use of resources, habitat conversion, siltation and land-based as well as sea-based pollution and contamination. In addition, extensive development projects in many lowland region which encourage mankind activities such as agriculture, industry, housing and infrastructure facilities resulting in a reduction of suitable land for development.

Soft soils usually have low bearing capacity and high compressibility characteristics. Many are sensitive, where the strength can be diminished by mechanical disturbance. These conditions need to be improved to avoid excessive settlement and to ensure the safety and stability of the built infrastructure and other facilities. With the scarcity of suitable land for development, the next available alternative is to expand the development in geotechnical challenging environment such as peat soil, soft soil and highlands. To enable the successful development and construction project on soft soil, it should be stabilized to improve its settlement and strength behaviour.

Presently, various ground improvement methods have been proposed and implemented on soft soils to improve the soil bearing capacity and minimize the settlement magnitude. In geotechnical engineering, ground improvement means to increase on soil shear strength and reduce soil compressibility and soil permeability through various methods such as Ground improvement, Stabilisation and Reinforcement.

A stone column (also known as granular pile) is a type of soil stabilisation methods used to increase soft soil bearing capacity, stable slope, reduce the settlement of loose fine graded soils, and accelerating the effects of consolidation by improving drainage path for pore water pressure dissipation. The benefits are acquired from partial replacement of soft soils through more efficient materials such as aggregate of stone, sand and other granular materials. Furthermore, stone columns are very permeable and act as vertical drains that facilitate consolidation process in soft soil improvement program. Additionally, stone columns also act as reinforcing materials to enhance the overall strength and stiffness of soft soil. The investigations of stone column behaviour in soft soil has been done by many researchers throughout the world.

The column filler material normally consists of stone aggregates generally between 20 mm to 75 mm, gravel and sand compacted into a vertical hole generally with 0.6 meter to 1.0 meter diameters and 15 meter to 20 meter depth. When columns are formed by granular fill, their load capacities depend largely on the strength of the filler material and the confining stress of the surrounding soil (Bergado *et al.*, 1996) Currently, studies on different substances used as stone column fillers have been conducted to evaluate the performance of stone column as improvement method such as fly ash, Silica-Manganese slag, Pulverized Fuel Ash (PFA) and limestone from quarry.

Lightweight aggregates are selective materials used in projects where excess from subgrade load is a problem. The materials help in reducing the dead load and lateral forces by over half in the assembly on the structure on soft soils. Lightweight aggregate fill is also used to reduce pressure behind retaining walls, to insulate underground structures and utilities, as a sub-base material for concrete and landscape pavers and as a stable drainage medium beneath soils.

1.2 Problem Statement

Soft soil poses serious problems in construction due to its long-term consolidation settlements and low bearing capacity although subjected to moderate load. In Malaysia, soft land deposits extend across the country and mostly in coastal areas. With the scarcity of land suitable for construction, the next option is to pursue development in geotechnical challenging environments such as wetlands or soft and highland areas. The soft soil conditions need to be improved to ensure stability and safety of the built infrastructure and other facilities.

Typical methods of soft ground stabilisation practiced in Malaysia are surface reinforcement, preloading and prefabricated vertical drain, used of piles, chemical stabilisation and stone or sand column. However, the design of stone column is still empirical, it is based on contractor experience and requires field trials before execution. No well-defined guidelines or codes are available. Other than that, the availability and sustainability of construction materials should also be considered. Thus, this work is suggested as part of the ground improvement trial program in looking into the possibilities of replacing normal aggregates of stone column methods with Lightweight Expanded Clay Aggregate (LECA) as a filler for soft clay ground stabilisation. In addition, LECA aggregate is environmentally friendly since it was produced using easily found raw material which is natural clay soil.

1.3 Objectives

The aim of this research is to evaluate the stone columns in compression behaviour when installed in soft clay. Apart from that, the effect of Lightweight Aggregates used as soil replacement material and column filler also will be examined. The specific objectives of this research are:

(a) To examine the physical and mechanical properties of Lightweight Expanded Clay Aggregates (LECA) used in this research.

(b) To evaluate the compressibility behaviour of LECA columns-raft installed in soft clay soil through numerical modelling.

(c) To develop physical modelling in small-scale laboratory tests for verification of numerical modelling.

(d) To establish design chart for settlement prediction of soft soil treated with LECA as a raft and columns.

1.4 Scope of Research

The primary purpose of this research is to examine the possibility of stabilizing soft clay soils that have caused problems during construction or resulted in poor performance of highway infrastructure in service using LECA aggregates as a soil replacement and stone columns. This research was conducted using numerical analysis and small-scale laboratory tests. The lightweight aggregates used in this study were supplied by LEXCA Sdn. Bhd. while the ‘L2B20 kaolin powder used in this study was supplied by Kaolin (M) Sdn. Bhd., based in Selangor, Malaysia.

Laboratory tests in accordance to British Standard (BS) and/or the American Society of Testing Material (ASTM) were used to test the LECA aggregates and kaolin to determine their characteristics. The physical and mechanical properties of LECA aggregate were determined from standard laboratory tests.

Numerical analysis was employed to investigate and evaluate the effect of LECA columns-raft on settlement behaviour under large loaded area. In addition, displacement evaluation through physical modelling and Particle Image Velocimetry (PIV) were also done to verify the numerical analysis.

1.5 Research Significant

There are little to no previous studies on Lightweight Aggregate used in soft soil stabilisation works. Lightweight fill is used primarily to reduce the overall weight in service embankment, thereby reducing the permanent stresses on foundations. Lightweight forestry by-products such as bark, woodchip and sawdust wastes from the timber industry have regularly been used as lightweight fills. Shredded waste tyres or bales can also be considered for the lightweight credit construction technique on soft soil. The most popular lightweight materials are the specifically manufactured lightweight products such as EPS (Expanded-Polystyrene Block Geofoam). The use of LECA as soil replacement and stone column as soil improvement method was introduced to solve settlement and stress problem in soft clay soil. Below are some of the major contributions of this research towards knowledge as well as the construction industry:

(a) Possibility of LECA aggregates used as column filler in soft soil stabilisation since there is no research conducted to study on this matter.

(b) Reduce settlements in pavements and embankments due to high compressibility of soft soil.

(c) Reduce time consuming on construction especially in filling work due to easy handling and compaction work of LECA material.

1.6 Limitation of Research

The scope of research is limited to analysis of LECA columns-raft effect on long term settlement behaviour under large loaded area. The numerical analysis was performed on LECA columns installed in the middle of the group, which is constrained laterally by other columns in all directions. Column at the edge of the group was not analysed. LECA columns are assumed to be 'wish in place', where possible smear effects caused by disturbance on the surrounding soil due to column installation effect is neglected. The interaction between soil and LECA column is also considered smooth. The granular raft is assumed as a rigid smooth layer through which uniform load is applied. The settlement behaviour of various configurations of stone column spacing and length is examined for 50 kN/m^2 uniform load. Other influenced parameters such as friction angle of column (ϕ_c), load intensity (p) and post installation lateral earth pressure (K_0) on settlement behaviour were not analysed. The diameter column is fixed at 700 mm diameter and the depth of soft soil layer is 10 meter.

1.7 Organization of Thesis

This thesis consists of seven chapters. The explanation of each chapter is as follows:

Chapter 1 generally describes the background of problems associated to the improvement of soft soils and also states the objectives, scope and limitation of the conducted study.

Chapter 2 briefs the review of literature in this study. The review covers the properties of soft clay and lightweight aggregate, and their applications in construction. The stone column method as soft soil stabilisation and numerical modelling implemented in geotechnical analysis also are discussed in details. Similar researches that have been conducted by previous researchers are also reviewed in this chapter.

Chapter 3 describes the research methodology which includes numerical modelling, testing programme and experimental modelling on small scale model tests to study the strength and compressibility of soft clay reinforced with LECA raft and LECA columns-raft. Details on the design of experimental setup, preparation of homogeneous clay samples and the construction of LECA column(s) are also discussed in the chapter.

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