BEHAVIOUR OF EXPANDED PILES IN CLAY UNDER UPLIFT AND COMPRESSIVE LOADING

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To my lovely wife, your courage and compassion have taught me humility

To my beloved parents

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ABSTRACT

Existing soil at construction site may not always be suitable for supporting structures. Hence, various techniques can be utilized to improve the shear strength, increase the bearing capacity, increase the factor of safety, and reduce the settlement, shrinkage and swelling of soft soils. Among the improvement techniques, preloading and radial preloading using prefabricated vertical drainage are two popular methods in order to improve soft soils. Recently, a new concept of radial preloading has been presented under the name of expanded piers or expanded piles. In this method, an expandable membrane is expanded by means of an injection of air pressure to make an expanded cylindrical cavity, and is filled with a suitable material such as concrete or sand. Thus, the expanded element and the surrounding soil provide a stiffer component compared to the untreated soil. The main focus of this study was an evaluation of the effect of the diameter ratio (DR= final diameter of membrane after expansion / initial diameter of membrane before expansion) on the load capacity of the pile under upward and downward loading. To achieve these aims, 18 physical modelling tests on white Kaolinite were carried out to determine the pile pull out capacity and bearing capacity of the piles. Hence, the diameter ratios of 1.5, 2 and 2.5 times the initial diameter of the cylindrical cavity were selected. In this study, two methods were used to perform the expanded piles, radial expansion and radial expansion with surcharge. A series of physical modelling was designed to assess the different behavior of these two methods. In addition, a series of numerical modelling, based on the soft soil and Mohr-coulomb model, were conducted to simulate the pile behaviour and verification of the laboratory results. Based on the obtained results in the pull out tests, a significant increase was observed in the load capacity equal to 86%, 132% and 153%, for diameter ratios equal to 1.5, 2, and 2.5, respectively, in the soft clay for expansion method. The increase in load capacity were equal to 170%, 175% and 183% for the same diameter ratios, performed by means of expansion with surcharge method. Similarly, in the cases of compressive loading, the load ratios were increased equal to 40%, 47% and 53%, for diameter ratios equal to 1.5, 2, and 2.5, respectively, for expansion method. The increase in load capacity were 99%, 82% and 69% for the same diameter ratios, performed by means of expansion with surcharge method. Moreover, results showed that with increase in the piles diameter equal to 33% and 66%, the load ratios were increased up to 46% and 86%, for expansion method in case of pull out tests. Meanwhile, the load capacities were increased up to 63% and 144% for the expansion method in case of compressive tests. Furthermore, the soft soil model can be considered to have good agreement to simulate pile behaviour under vertical loading with the effect of radial preloading.

ABSTRAK

Tanah di tapak pembinaan yang sedia ada mungkin tidak selalunya sesuai untuk menyokong struktur pembinaan. Oleh itu, pelbagai teknik telah digunakan untuk meningkatkan kekuatan ricih tanah lembut, keupayaan galas, faktor keselamatan dan mengurangkan pengecutan serta pengembangan tanah. Antara kaedah pembaikan tanah, prapembebanan mendatar dengan menggunakan saliran menegak pasang siap adalah dua kaedah yang popular untuk meningkatkan kekuatan tanah lembut. Kebelakangan ini, konsep prapembebanan mendatar telah dijalankan dengan cara tetiang berkembang atau cerucuk berkembang. Dalam kaedah ini, membran dikembangkan dengan menggunakan tekanan udara bagi mengembangkan rongga silinder dan diikuti dengan prosess pengisian dengan mengunakan bahan- bahan yang sesuai seperti konkrit atau pasir . Oleh itu, membran tersebut dan tanah sekitarnya akan menjadi komponen yang lebih keras berbanding dengan tanah yang tidak dirawat. Tujuan utama kajian ini adalah untuk menilai kesan prapembebanan mendatar dalam nisbah garis pusat (DR = diameter membran selepas pengembangan / diameter membran sebelum pengembangan) terhadap keupayaan cerucuk di bawah pembebanan secara menegak keatas dan ke bawah. 18 ujian pemodelan fizikal telah dijalankan terhadap Kaolinit untuk menentukan keupayaan tarik keluar dan keupayaan galas cerucuk. Oleh itu, nisbah diameter 1, 5, 2 dan 2.5 kali garis pusat awal rongga silinder telah dipilih. Dalam kajian ini, dua kaedah telah digunakan untuk menghasilkan cerucuk berkembang, pengembangan mendatar dan pengembangan mendatar dengan surcaj. Satu siri pemodelan fizikal telah diadakan untuk mengaji kelakuan kedua-dua kaedah tersebut. Di samping itu, satu siri model fizikal yang berdasarkan tanah lembut dan model Mohr- Coulomb diadakan untuk mensimulasikan kelakuan cerucuk dan pengesahan data makmal. Berdasarkan keputusan yang diperolehi dalam ujian tarik keluar, peningkatan yang ketara telah diperhatikan dalam kapasiti beban bersamaan dengan 86% , 132 % dan 153 %, untuk nisbah diameter 1,5 , 2, dan 2.5 bagi kaedah pengembangan tanah liat lembut. Peningkatan kapasiti beban adalah sebanyak 170%, 175 % dan 183 % bagi nisbah diameter yang sama, yang dilakukan dengan cara pengembangan dengan kaedah surcaj. Begitu juga, dalam kes-kes pembebanan mampatan , nisbah beban bertambah sebanyak 40 % , 47% dan 53 %, untuk nisbah diameter sama dengan 1,5 , 2, dan 2.5, bagi kaedah pengembangan. Peningkatan kapasiti beban adalah 99%, 82% dan 69 % bagi nisbah diameter yang sama, dilakukan dengan menggunakan kaedah pengembangan dengan surcaj. Selain itu , keputusan menunjukkan bahawa dengan peningkatan diameter cerucuk yang bersamaan dengan 33% dan 66 % , nisbah beban telah meningkat sehingga 46% dan 86 %, bagi kaedah perkembangan dalam kes ujian tarik keluar. Sementara itu, kapasiti beban telah meningkat sehingga 63% dan 144 % bagi kaedah pengembangan dalam kes ujian mampatan. Selain itu, model tanah lembut merupakan model yang paling sesuai untuk mensimulasikan kelakuan cerucuk dibawah bebanan menegak dengan kesan pra-bebanan mendatar.

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LIST OF ABBREVIATION

AASTO	-	American Association Of State Highway And Transportation Officials
ASTM	-	American Society For Testing And Materials
BS	-	British Standard
CPT	-	Cone Penetration Test
CRP	-	Constant Rate of Penetration
CSL	-	Critical State Line
CU	-	Consolidated Undrained
DR	-	Diameter ratio
LL	-	Liquid Limit
LR	-	Load ratio
LVDT	-	Linear variable different transducer
MC	-	Mohr-Coulomb
OCR	-	Over consolidation ratio
PI	-	Plasticity Index
PL	-	Plastic Limit
PLC	-	Pull out test large diameter with top coverage
PLE	-	Pull out test large diameter with expanding method
PLW	-	Pull out test large diameter without expanding
PMC	-	Pull out test medium diameter with top coverage

PME	-	Pull out test medium diameter with expanding method
PMW	-	Pull out test medium diameter without expanding
PSC	-	Pull out test small diameter with top coverage
PSE	-	Pull out test small diameter with expanding method
PSW	-	Pull out small diameter without expanding
PVD	-	Prefabricated vertical drainage
QML	-	Quick Maintained Load
RAP	-	Rammed Aggregate Pier
SL	-	Shrinkage Limit
SLC	-	Settlement test large diameter with top coverage
SLE	-	Settlement test large diameter with expanding method
SLW	-	Settlement test large diameter without expanding
SMC	-	Settlement tests medium diameter with top coverage
SME	-	Settlement test medium diameter with expanding method
SMW	-	Settlement tests medium diameter without expanding
SRR	-	Settlement Reduction Ratio
SS	-	Soft soil constitutive model
SSC	-	Settlement test small diameter with top coverage
SSE	-	Settlement test small diameter with expanding method
SSW	-	Settlement test small diameter without expanding
UAP	-	Unrammed Aggregate Pier
US	-	United States

LIST OF SYMBOLS

A_{si}	-	Pile Skin Area in the First Layer
a_1	-	Coefficient of ratio of tip resistance to shaft resistance related to expanding condition
a_2	-	Coefficient of ratio of tip resistance to shaft resistance related to top coverage condition
c	-	Cohesion
C_c	-	Compression index
C_k	-	Permeability Index
C_p	-	Compressibility Index
C_s	-	Swelling index
C_v	-	Coefficient of consolidation
c'	-	Effective Cohesion
e	-	Void Ratio
D	-	Diameter of pile
D_m	-	Diameter of pile model
D_p	-	Diameter of pile prototype
E	-	Elastic modulus of soil
E_0	-	Oedometer Elastic modulus
E_m	-	Elastic modulus of model
E_p	-	Pile Elastic Modulus and Elastic modulus of prototype
E_s	-	Soil Elastic Modulus
e_o	-	Initial void ratio

e_i - Initial Void Ratio

e_f - Final void ratio

F - Force

F_{cb} - Base Resistance Factor

F_{ct} - Total Resistance Factor

F_m - Force for model

F_p - Shear modulus

G - Shear modulus of soil

G_s - Specific Gravity

g_m - Ground acceleration for model

g_p - Ground acceleration for prototype

H_i - Total Height

H_f - Final Height

I - Electrical current

I - Inertia moment

I_m - Inertia moment for model

I_r - Rigidity in the cavity expansion

I_p - Inertia moment for prototype

K - Temperature

kN - Kilo Newton

kPa - Kilo Pascal

L - Length of pile

L_m - Length of pile for model

L_p - Length of pile for prototype

M	-	Mass
m_m	-	Mass for model
m_p	-	Mass for prototype
m/s	-	Meter/Second
mm	-	Millimetre
P′	-	Effective Mean Stress
p_u	-	Ultimate pressure inside the cavity
q	-	Deviator Stress
Q_p	-	Bearing capacity of the pile tip
Q_{p_C}	-	Bearing capacity of the pile tip for top coverage method
Q_{p_E}	-	Bearing capacity of the pile tip for expanding method
Q_{p_W}	-	Bearing capacity of the pile tip for without expanding
Q_s	-	Bearing capacity of shaft
Q_{s_C}	-	Bearing capacity of the pile shaft for top coverage method
Q_{s_E}	-	Bearing capacity of the pile shaft for expanding method
Q_{s_W}	-	Ultimate bearing capacity of the pile shaft for without expanding
Q_{ult}	-	Ultimate bearing capacity
Q_{ult_c}	-	Ultimate bearing capacity of the pile for top coverage method
$Q_{ult_{p_C}}$	-	Ultimate bearing capacity of the pile tip for top coverage method
$Q_{ult_{s_C}}$	-	Ultimate bearing capacity of the pile shaft for top coverage method
Q_{ult_E}	-	Ultimate bearing capacity of the pile with expanding method
$Q_{ult_{p_E}}$	-	Ultimate bearing capacity of the pile tip for expanding method
$Q_{ult_{s_E}}$	-	Ultimate bearing capacity of the pile shaft for expanding method
Q_{ult_W}	-	Ultimate bearing capacity of the pile without expanding

$Q_{ult_{p_w}}$	-	Ultimate bearing capacity of the pile tip without expanding
$Q_{ult_{s_w}}$	-	Ultimate bearing capacity of the pile shaft without expanding
Q_p	-	Bearing capacity of the pile tip
Q_{p_C}	-	Bearing capacity of the pile tip for top coverage method
Q_{p_E}	-	Bearing capacity of the pile tip for expanding method
Q_{p_w}	-	Bearing capacity of the pile tip for without expanding
Q_s	-	Bearing capacity of shaft
q	-	Initial ground stress (chapter 2-cavity expansion theory section)
q_{sik}	-	Characteristic Value of the Skin Friction per unit Area in the First Layer
R	-	Radius of cavity
R_b	-	Comparative Settlement Symbol
R_{bk}	-	Toe resistance
R_{ck}	-	Total bearing capacity
R_i	-	Initial radius of cavity
R_p	-	Radius of the plastic zone in cavity
R_s	-	Settlement Reduction Ratio
R_{sk}	-	Skin Friction
r	-	Radius of pile
r_m	-	Radius of pile for model
r_m	-	Radius of pile for prototype
S	-	Degree of Saturation
S	-	Settlement
S_m	-	Settlement of model
S_p	-	Settlement of prototype

S_{tip}	-	Settlement at the Tip of Pier
S_{top}	-	Settlement at the Top of Pier
S_u	-	Undrained Shear Strength
T	-	Time
T_m	-	Time for model
T_p	-	Time for prototype
u_p	-	Pore water pressure at the plastic zone
V_i	-	Total volume
V_f	-	Final volume
ν	-	Poisson's Ratio
ω	-	Moisture Content
γ	-	Unit Weight
γ_d	-	Dry density
γ_s	-	Saturated density
φ	-	Friction Angle
Φ'	-	Effective Friction Angle
Ψ	-	Angle of dilatancy
%	-	Percent
σ	-	Normal Stress
κ^*	-	Modified swelling index
λ	-	Scaling factor
λ^*	-	Modified compression index
Δu	-	Excess pore water pressure
$\sigma_\circ$	-	Applied mean normal stress

σ_p	-	Radius stress at plastic zone
σ_r	-	Radius stress
σ_θ	-	Tangent stress
ν_{ur}	-	Poisson ratio for unloading reloading
ρ_m	-	Density of model
ρ_p	-	Density of prototype

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Concurrent with the development of human societies, construction of buildings, embankments, storage silos, bridges on soft soils is inevitable. In the meantime, new methods and innovations play important role to improve problematic soils, especially soft clay. Often, new approaches involve lower final price, greater ease and reduced time. Among known soil improvement methods such as stone columns, compaction grouting, compact rammed aggregate piers, installing auger cast pile, tapered displacement piles, pressure-inject piles and helical piers, use of the methods according to radial preloading concept have been recently noticed by engineers because of the mentioned benefits. These methods relate to a method and apparatus for reinforcing soil by improving the stiffness of soil to limit vertical settlement and increase bearing capacity. This invention, which is called expanded pier or pile can be installed in greater depths in comparison with similar methods. In addition, the cost of the performance of these piers is significantly less than utilizing aggregate piers or similar reinforcing mechanisms.

In practice, radial preloading refers to prefabricated vertical drainage system known as prefabricated vertical drainage (PVD) (Binder, 201; Almeida *et al.*, 2000; Dhar *et al*.). Recently, however, another immersion concept has been introduced by US. Patent NO 6354768 by Fox in 2002. This patent has suggested a new technology for soft soil improvement. In this method, an expandable membrane is inserted in the soft ground and expanded several times its initial cross-sectional area or to any desired diameter using air, slurry, sand, foam, gas, liquid, solid substance, composition or another combination. The shape and dimension of the cavity can vary desired. Due to radial expansion, the surrounding soil is densified, stressed and strained radially, thereby shear strength and vertical stiffness is significantly increased. In this way, the settlement of the surrounding soil of the expanded membrane is reduced and also bearing capacity of the pile is increased. Figures 1.1 shows an expandable membrane before and after expansion.

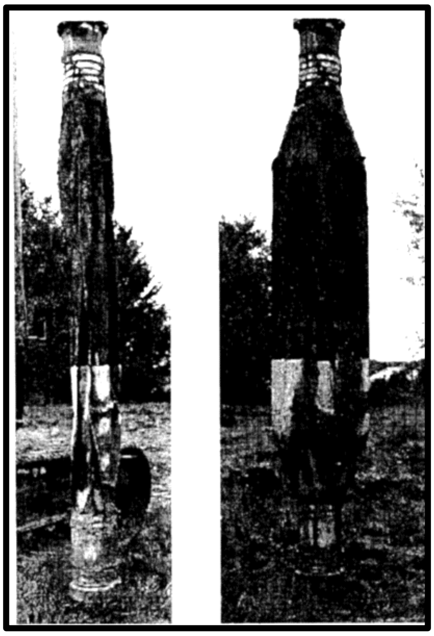

Figure 1.1 Expanded Pier before and after expansion (Geopier, 2003)

The invention can, however, be utilized to stiffen clays, silts, loose sands, peats and organic soils. When preload piers are installed as a group, they are expected to improve the surrounding soil matrix through densification and consolidation. As mentioned, this method would be highly desirable as an improved method and apparatus for increasing the stiffness of soil at a depth of up to one hundred and fifty feet and at a cost which is significantly less than the cost of utilizing aggregate piers or other soil reinforcing systems. The cost per foot of building is 15% to 30% cheaper than aggregate pier. The stiffness of each cell is five to twenty times greater than the stiffness of the soil. Furthermore, it can be utilized to stiffen clays, silts, sands which are harder and denser than said soft clays, soft soils, and loose sand; it can also be utilized to stiffen peat and organic soils and landfills; and can be used to generate stresses and strains in almost all types and classifications of soils.

In fine cohesive soils such as soft clays, radial expansion causes radial consolidation. Due to this consolidation, excess pore water pressure is increased. Over time, effective mean stress is increased due to dissipation of pore water pressure and consequently, soil stiffness is enhanced and settlement can be decreased. It should be noted that the effective stress is considerably reduced with increasing the distance from the centre of the pier.

Depending on the foundation which is used, the settlement can be uniform (Choobbasti *et al*., 2011), or non-uniform such as embankments. In these cases, a section of the applied load is transferred by piers and the other section is directly transferred by the surrounding soils. Indeed, the vertical load is distributed into two parts, the first part directly on the pier, and the second part on the surrounding soil. Depending on the stiffness of the piers and surrounding soils, one pier can be considered as a single pile or as a part of the soil improvement system (Been and Sills, 1981). The ratio between stresses, which are divided between the column and surrounding soil, can be constant with increasing displacements in different piers such as compaction columns (Kirsch and Sondermann, 2001). At the boundary of the pier group, deformation in the horizontal direction is zero when all of columns are loaded.

Another factor that can affect on the distribution of load between soil and piles is the spacing between the piles. In the expanded pile group, the optimum spacing of preload piers increase with increasing soil stiffness and final radius of expanded piers. The cell has a stiffness which typically, but not necessary, is two to ten times the stiffness of the soil in which membrane is utilized. The shortest distance between each pair of cavities is about one to ten feet. The maximum diameter or width of each cavity is about six to forty-eight inches. Membranes extend to depths of two hundred feet if the aggregate pier was comprised of cavity and tamped.

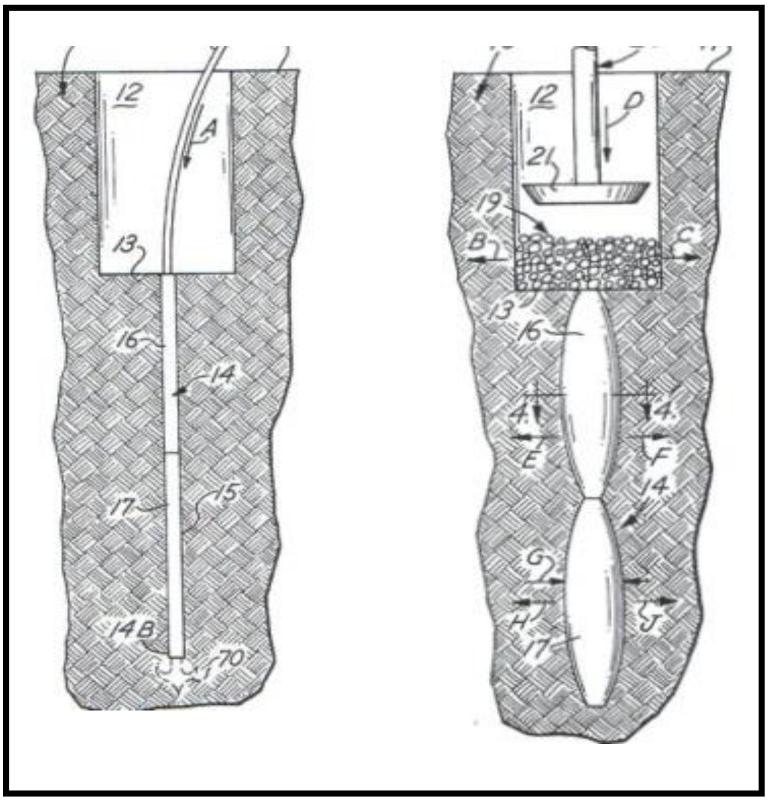

Figure 1.2 Performance method of expansion pile with surcharge (Fox, 2002).

Cavity expansion theory can be interpreted as well as this technique which there are reliable finite element methods solutions. Based on these solutions, stress changes with the increasing radial distances from the centre of the expanded cavity, in similar conditions for pile driving. This theory can also be used to solve other geotechnical problems such as a cone penetrations, explosion, or grout injection in the soils.

1.2 Problem Statement

Low bearing capacity of the piles, which are subjected on the upward and downward loading, is one of the most important problems in the construction of buildings, embankments, water storages, and bridges in soft soils, particularly in soft clayey soils (Nazir and Azzam, 2010; Shanker *et al.* 2007; Stuedlein and Holtz, 2012). Moreover, increasing the shear strength and vertical stiffness for control of the settlement are the most important concerns of civil engineers (Santagata *et al*., 2005; Liao *et al*., 2006).

In another aspect, traditional improvement soft soils methods such as pile driving, bored piles, stone columns and rammed aggregate piers have been intensely studied, and their fundamental concepts have been identified (Fellenius,1999; Van Impe, 2008; Chin and Meng, 2003; Hunt *et al*., 2002). Currently, several new concepts have been developed by a number of engineers in recent years such as radial preloading using innovative methods (Biringen and Edil, 2003). Some aspects of radial preloading methods such as radial consolidation effects and changes in the shear strength and stiffness in the horizontal and vertical direction on the surrounding soil have been fully studied (Handy and White, 2006b; Xiao *et al.*, 2011; Randolph *et al*., 1979).

Furthermore, the main focus of laboratory experimentation was on the effect of the pile driving or performance of the piles (Handy and White, 2006a; Yin and Fang, 2010; Bian, *et al.* 2008). As mentioned earlier, the main function of expanded piers is the densification of surrounding soil, which have been studied by the other researchers, completely, as mentioned in the previous section. Meanwhile, there is no research on the settlement and bearing capacity on the expanded pier not on the soil. Nonetheless, no research on the variation of the piles behaviour under vertical loading for piles have been performed by expanded piles method. Therefore, it is important to fully understand the variation of the load capacity in the case of pull out and compressive conditions for different performance methods on side friction.

1.3 Objective of Study

The main purpose of this study is to investigate pile behaviour under vertical loading including drag and compressive conditions due to radial preloading in soft clay. A series of physical modelling on a small scale were conducted on rigid and floating piles with different performance methods including without expansion, with expansion and expansion with surcharge to evaluate two issues consisting of expanded diameter ratio on the pile pull out capacity and load capacity. The results of the physical modelling were validated by finite element from different aspects in order to predict and apply the results to actual problems. In order to achieve the above aims, the following objectives have been mentioned.

1) To demonstrate the effect of radial preloading on the load capacity of the expanded pile.
2) To study the effect of the surcharge on the load capacity of the expanded pile due to radial preloading.
3) To investigate of the increase of pile diameter on the load capacity of the pile based on the different performance methods involving without expansion with expansion and with surcharge methods.
4) To compare different criteria for pile bearing capacities to evaluate of the effect of radial preloading in compressive loading for different performance methods.
5) To simulate of the pile behaviours based on the different performance methods in order to select the suitable constitutive model using a finite element software.
6) To validate the numerical model and modelling physical experiment based on the performance methods and pile diameter increase.

1.4 Scope of the Study

To achieve the mentioned goals in the previous section, eighteen physical modelling and thirty six numerical modelling were conducted on a straight single floating pile on white Kaolin as a soft clay. In each case, three piles with an equal length and different diameters were compared with three piles with same length and with an equal initial diameter, and final diameters equal the first group of piles, which were subjected on the radial preloading, for two different performance methods and different loading conditions. Based on the mentioned aims and conditions the following scopes were considered during this research.

1) Only a single pile was intended to study of pile behaviour under vertical loading due to radial preloading. In practice, expanded piles could be utilised alone or as a group of improvement elements.

2) In this research, piles were subjected to vertical loading.
3) Soft clay has been assumed as a saturated clay with undrained behaviour during vertical loading and drain behaviour during consolidation process.
4) Soil was homogenous as an ideal condition.
5) In this investigation, it was assumed that the pile is straight and vertical.
6) In this research, only floating piles were simulated.
7) In order to simulate of the pile behaviours, an effective stress analysis was considered because of drained behaviour of the soil during consolidation process. It is necessary to say that the behaviour of piles under vertical loading step were undrained.

1.5 Limitations of Research

In this research, normally saturated consolidated soft clay was improved by an expanded pile which was formed by a cavity expansion and filled by light concrete. There are some limitations which were dealt with during this study as follows:

1) In the physical modelling, a complete cylindrical cavity should be formed. However, an expandable rubber membrane was utilized as a radial preloading device, and as a result the shape of the cavity could not be exactly the same as a cylindrical cavity.
2) In the numerical modelling, a prescribed displacement was used to form a cylindrical cavity. However, in practice this shape cannot be formed as a cylindrical cavity, exactly.
3) As an undrained shear strength of 10 kPa had been intended for soft clay, it cannot completely represent soft clay. On the other hand, more soil stiffness can be considered to exactly and completely develop the obtained results.
4) As an effective analysis should be considered to simulate the soil behaviour of the pile in the soft soil model in the software, the triaxial test could not be conducted on very soft clay. However, in this research a modified method for installation of the soft clay in the triaxial test device was introduced to apply for soft clay with at least 10 kPa for undrained shear strength.

5) It is preferred that a strain control method be used to obtain the load-displacement curves for compressive tests, while in this study a stress control method was utilized. However, for the pull out tests, a strain control method was considered.
6) In physical modelling in order to simulate of the surcharge effect a rigid plate was considered instead of the upper layer of the soil on the pile. It necessary to say that the behaviour of the soil I the field is on the stress control, while in the model is on the stress control.

1.6 Significance of Research

In recent years, the engineering community has proposed new alternative methods to improve soft soils. These methods should be more applicable, economical, and easy to perform and save time. Accordingly, using radial preloading concept is more noticeable by designers and employers. The previous researches in the literature are mostly concerned with load capacity of vertical piles and the effects of pile driving on the surrounding soils (Randolph *et al.*, 1979). In another respect, variation in soil stiffness has been investigated on the surrounding soils due to radial preloading (Biringen, 2006). In addition, some studies have focused on the radial expansion of surrounding soil due to performance of aggregate piers such as stone columns. (Zahmatkesh and Choobbasti, 2010). As can be seen there is no investigation on pile bearing capacity or pull-out capacity behaviour, which has been performed directly after radial preloading. In this research, the main focus was on the effect of radial preloading on pile behaviour in several aspects. The following benefits can be derived from this research:

- Based on the obtained results of this study, more realistic design can be conducted to improve soil mechanism by expanded piers to reduce settlement and increase pile pullout capacity and bearing capacity.
- The results of this research can be used to obtain a general idea from which to choose the expansion diameter ratio in the radial preloading to design expanded piles under vertical loading including compressive or tensile loading.

- The presented study includes the effects of two different performance methods. Accordingly, the most suitable method can be selected based on the concluded results of the practical design parameters, such as selection of the suitable diameter for piles, best expansion ratio, and best performance method.
- Another finding of this research is which constitutive model can be more suitable to simulate the pile behavior under vertical loading due to radial preloading. In addition, the selected model can be used to predict of pile behaviour for different conditions.
- A comparison study was conducted to determine the effect of the selection of the criteria for compressive loading. Based on the results, a designer can choose the best criteria for pile-settlement behavior during the calculation of practical parameters of expanded piles in practice.

1.7 Organization of Thesis

To meet the mentioned objectives, this thesis presents the results of a series of experimental and numerical modelling to develop an understanding of the influence radial preloading on pile under vertical loading in two main sections including pile bearing capacity and pile pullout capacity. In each section a series of physical modelling in laboratory size were conducted on very soft clay with shear strength equal to 10 kPa. Each physical modelling was verified by two different numerical modelling including Soft Soil model and Mohr-Coulomb model in order to find the best model to simulate pile behaviour from different aspects which coincide with real pile behaviour under various expansion radius. In the section dealing with pile bearing capacity and pile pullout capacity, three aims were followed. First, the expansion diameter ratio was studied to evaluate variations of pile bearing capacity and pile pullout capacity. Second, the same parameters were investigated for the same piles with the same different expansion ratios. However, in this section the heave of the surrounding soil of the pile due to radial preloading was disregarded by using a layer of surcharge. In the third section, three piles with different diameters were compared to three other piles with same specifications, but different performance methods. In addition, a series of basic tests including initial and supplementary tests were carried out to obtain the soil parameters for physical and numerical modelling.

Based on the foregoing, this thesis consists of 6 chapters and the essence of each chapter is as follows:

Chapter1 includes a background of the problem associated with the improvement of soft soils by radial preloading and states the objectives, scopes, and significance of study in this research. Chapter 2 reviews the literature of the preloading method to improve soft soils, the cavity expansion theory, which supports this study and expanded piles as an improvement element. Moreover, fundamental concepts including shear strength, soil stiffness, pile bearing capacity, pullout capacity are described to clarify the basic concepts in this study. Chapter 3 describes research methodology in detail. Material of testing, equipment, measurement methods, instrumentations are addressed in this chapter. In addition, model testing including details of the design and performance of physical modelling setup, supplementary tests, and scaling factors are explained. Experimental modelling, including the organization of the physical modelling, results of the load-displacement curves and basic tests results are presented in Chapter 4. The results of the numerical modelling, including the simulation of experimental modelling based on two numerical models and a validation of the numerical model and model of physical experiment are depicted in Chapter5. Chapter 6 summarizes the contributions, outcomes, and conclusion of this study. In addition, a series of recommendations are stated for future researches.

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