DEVELOPMENT OF SIMPLIFIED DESIGN TECHNIQUES FOR ESTIMATING UNDRAINED BEARING LOADS OF PILED-RAFT IN SOFT CLAY

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Project Supervisor: Ir. Dr. Chan Swee Huat

DECLARATION

I solemnly declared that this research project work has been done by me and supervised by my main project supervisor - Ir. Dr. CHAN Swee Huat.

Lastly, this thesis has not been presented to any other universities for any degrees.

Declared by :

Er. Tan Kim Leong

Professional Engineer (Singapore)

Chartered Professional Engineer (ASEAN)

ACKNOWLEDGEMENT

I wish to dedicate this thesis to my beloved wife (Ms. Toh Ian Lee) for her strong supports and motivations and my dearest little princess (Tan Hy Jeu) for their love and patience, and not forgetting my dearly old parents and loving siblings.

This dissertation would not have been possible without the assistance, support and encouragement of many wonderful people to whom I wish to convey my sincere appreciations.

I wish to express my deepest gratitude to my Year 1 Internal Assessor Dr. Song Ki-ll, Year 2 Internal Assessor Dr. Song Myung Kyu, co-supervisors Dr. Mostapha Boulbibane and Dr. Sandy Kok, all from the Department of Civil Engineering.

On special note, I wish to put across my upmost appreciation and gratefulness to Ir. Dr. Chan Swee Huat as being my main project supervisor and for his invaluable guidance, inspiration and unstinting supports.

Finally yet importantly, I would like to thank the prestigious University of Nottingham for their kindness and generous scholarship given which helps to see me through the programme successfully.

DEDICATION :

To my beloved family and extended family.

Especially to my dearest little princess (Tan Hy Jeu).

PUBLISHED INTERNATIONAL JOURNAL & TECHNICAL PAPERS

(with peer-reviewed)

1. "SUSTAINABLE DESIGN TECHNIQUES FOR FOUNDATION STRUCTURE – *green initiative!"* – INTERNATIONAL JOURNAL OF STRUCTURAL ANALYSIS & DESIGN, IJSAD, Volume 1: Issue 2 [ISSN: 2372-4102] on 25 June 2014;

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3. SUSTAINABLE DESIGN FOR PILED-RAFT FOUNDATION – *green initiative!"* – 18TH IABSE (INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERS) CONGRESS @ *KOREA-SEOUL IN SEPTEMBER 2012*;

4. "SUSTAINABLE DESIGN FOR UNPILED-RAFT FOUNDATION STRUCTURE" - THE 2ND INTERNATIONAL CONFERENCE ON REHABILIATION AND MAINTENANCE IN CIVIL ENGINEERING @ *INDONESIA-SOLO IN MARCH 2012.*

Review

Keywords: *load-bearing and settlement curves; short-term differential settlement; soil-structure interactions; simplified design; total permissible load; raft foundation and piled-raft foundation.*

The thesis subject serves to provide simplified engineering guidance from the perspective of providing quick preliminary design and assessment control to achieve optimization engineering design.

Objectives

The objectives of this research are to:-

a) Investigate the undrained bearing capacity and vertical settlement behaviours of raft and piled-raft in the soft clay using 3-D finite element analyses;

b) Compute the bearing capacity contribution by the raft through various simulation from the loaded piled-raft models;

c) Develop simplified design techniques to permit a quick preliminary assessment and design of raft and piled-raft foundation for project planning & cost estimation purpose, and safety and risk analysis study;

d) Develop design pedagogies with self-explanatory design flowcharts, step-by-step procedures together with some worked examples on the raft and piled-raft foundations design to allow learning and practice.

Limitation on Rapid Foundation Assessment Avenue

There are limited versatile foundation design charts and tables readily available at the present moment, especially with range of information on foundation bearing capacity at 25mm settlement. Such information would allow engineers to perform a quick preliminary assessment on a square foundation with sizes ranging from five to twenty square metres (for both raft and piled-raft foundations).

In addition, the existing equivalent raft concept formula for calculating the bearing capacity of a piled foundation does not take into account the following factors:-

i) interaction between the pile-raft-soil

ii) number of piles

iii) length of piles

iv) spacing of piles

In general, these newly developed foundation design charts (Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5) and design table (Table 7.2.1) come collectively with the efficiency of the raft's contribution from the piled-raft foundation.

Through this research study, some simplified design techniques, design pedagogies with flowcharts, and worked examples are developed and presented in this thesis.

Scope of Work

The research work focuses on soil-structure interaction, undrained soil bearing capacity and vertical settlement behaviours of both raft and piled-raft foundations in soft clay soil overlying a layer of firmer clayey soil. The following range of parameters are considered but not limited to :-

- Raft size : 5m x 5m, 10m x 10m and 20m x 20m foundations
- Pile size: 250mm square precast reinforced concrete piles
- Pile length : 12m , 24m and 36m
- Pile centre-to-centre spacing : 2m and 3m at square-grid arrangements
- Normal consolidated undrained shear strength of 40m thick soft clayey soil at top layer : 10kPa, 20kPa, 30kPa and 40kPa
- Normally consolidated undrained shear strength of 20m thick firm clayey soil at bottom layer : 140kPa
- All simulated loads are uniformly distributed on the raft
- Bearing capacity considered at short-term settlements : 10mm and 25mm *(however, focus would be on 25mm settlements)*

Methodology

A piece of commercial software, PLAXIS 3D FOUNDATION program developed by PLAXIS, is used as the numerical tool to aid the simulation and analysis of the computation work. This three-dimensional PLAXIS program, which is developed for the analysis of foundation construction, is widely used for the foundation, tunnelling and offshore structure engineering works. It is part of the PLAXIS product range, a suite of finite element programs, which are used widely for geotechnical engineering design.

The Building Construction Authority (BCA) in Singapore has also approves this geotechnical engineering design software.

Evaluation of the Works on the New Developments (Design Charts and Design Table)

Numerical results obtained from the Plaxis are used to develop some simplified design charts to serve as a quick design guide and reference for both the raft and piled-raft foundations under short-term settlement. Together with these newly developed design charts, they are further used to develop into a design table for calculating the bearing capacity.

Evaluation of these new developments are done by comparison with elastic solutions using elastic displacement method since elastic theory has been found to be useful for evaluation of immediate settlement for cohesive soil (*U.S. Army Corps of Engineers, Settlement Analysis, 1994).*

Recapitulation on the Work Done (Figure 1.1.1)

i) Phase 1 of 5 : Raft Foundation

The main objective is to study the bearing capacity of raft foundation against vertical settlement and its behaviours to develop some design charts and design table. Wide range of raft foundations (5m x 5m, 10m x 10m, 20m x 20m) constructed on different soil parameters are considered and used in the analyses work and subsequently used to develop the short-term bearing capacity against settlement design chart (Fig. 4.2.4) with design flowchart, guiding steps and some worked examples for completeness.

In Phase 1 work, it is found that the smallest (5m x 5m) raft foundation managed to achieve the highest bearing capacity. Details of the desktop studies, findings and conclusions are covered in this thesis. All works are conducted with the use of the results from the 3D FEM geotechnical software. These results are further evaluated with some theoretical calculations for rationalization purpose.

ii) Phase 2, 3 & 4 : (5m x 5m, 10m x 10m & 20m x 20m) Piled-Raft Foundation

The desktop studies focus on three different sizes of piled-raft foundations. Based on the work done in Phase 1, it is noted the smallest raft foundation has produced the highest bearing capacity against settlement.

The three different piled-raft foundations are modelled with varieties of raft configurations and soil parameters similar to the completed work done under Phase 1. New parameters included in the studies are :-

1) number of piles;

2) length of piles;

3) spacing of piles.

These would allow vis-a-vis comparisons made between the same sizes of raft and piled-raft foundations on the investigation work to allow study of any significant contribution from the slab in the piled-raft foundation.

Under Phase 2 to 4, the undrained soil bearing capacity of foundation against settlement design charts (Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5), together with methodology flowcharts, guiding steps and some worked examples are established and developed for completeness. All works are conducted with the use of the analysed results from the 3D FEM geotechnical software. Elastic solutions are used to evaluate these developments for rationalisation purpose. Details of the desktop studies, findings and conclusions are covered in this thesis.

iii) Phase 5 of 5 : Concluding

Works in this phase focused on consolidating and finalising of the research work from Phase 1 to 4.

The works in this phase include the collation and amassing of all the works done in this research project to produce :-

1) a simple yet versatile design charts *(Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5);*
2) a design table *(Table 7.2.1)*,

to permit a quick preliminary assessment and design of piled-raft foundation for project planning & cost estimation purposes, safety and risk analysis study.

With these presentations, the objectives of the proposed and accepted research project have been conducted, explored, established, evaluated, published and accomplished successfully.

Overseas Peer-Reviewed and Publications

To ensure that the research work done is of novel and acceptable quality, new and original, abstracts, technical papers and journal paper have been prepared and submitted to several reputable overseas international conference and congress for their technical committee to review, assess and comment, and finally for acceptance and publications.

Indeed, all phases of the works done have been privileged to be peer-reviewed by international experts, recognised, accepted and published by the established overseas international conference, and congress as well as journal :

1. "SUSTAINABLE DESIGN TECHNIQUES FOR FOUNDATION STRUCTURE – *green initiative!"* – INTERNATIONAL JOURNAL OF STRUCTURAL ANALYSIS & DESIGN, IJSAD, Volume 1: Issue 2 [ISSN: 2372-4102] on 25 June 2014;
2. "SUSTAINABLE DESIGN TECHNIQUES FOR FOUNDATION STRUCTURE – *green initiative!"* – CSBE 2014 (INTERNATIONAL CONFERENCE ON ADVANCES IN CIVIL, STRUCTURAL, ENVIROMENTAL & BIO-TECHNOLOGY), USA @ *MALAYSIA-KUALA LUMPUR IN MARCH 2014;*
3. "SUSTAINABLE DESIGN FOR PILED-RAFT FOUNDATION – *green initiative!"* – 18TH IABSE (INTERNATIONAL ASSOCIATION FOR BRIDGE AND STRUCTURAL ENGINEERS) CONGRESS @ *KOREA-SEOUL IN SEPTEMBER 2012;*
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Significance of This Research ~ *simplified design techniques*

Many structures founded on pile-raft foundations on soft clay in Singapore has been conservatively designed without considering the contribution from the raft due to the lack of knowledge (and thus design confidence) on the soil-structure interaction, bearing capacity of foundation against settlement. This generally resulted in very expensive foundation costs particularly in the soft clay conditions.

In view of the increasingly high prices of construction materials globally, it is timely to look into the development of an optimum design that provides safe, lasting and leaner design, allows use of resources effectively, economically and yet performing pile-raft foundation system efficiently in the soft clay condition. To achieve these, a thorough understanding of the soil-structure interaction, bearing capacity and settlement behaviours of piled-raft foundations in soft clay are of paramount importance.

This research is identified as being of importance to practical civil and structure engineers in providing them with simplified techniques to perform a quick preliminary assessment and design of piled-raft foundation, before carrying out complicated and time-consuming 3-D finite element analyses. This is particularly useful when a quick assessment of the feasibility and construction costs of piled-raft foundation is required during the preliminary design stage.

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CHAPTER 1

INTRODUCTION

CHAPTER 1: INTRODUCTION

1.1 Simplified Framework for this Research Work

This chapter presents the general approach on the philosophies and methodologies adopted in this research study and could best be demonstrated with a simple flowchart illustrating their key aspects in the respective chapters as shown in Figure 1.1.1.

Intention of this structural framework is to provide a summary account on the flow of sequences and thoughts that helped to facilitate and led to the research objectives, detailed works and ultimately arriving at the findings and conclusions.

The documentation of the detailed work with explication on each KEY STEP or the so-called "PHASE" work would be further elaborated in their respective chapters.

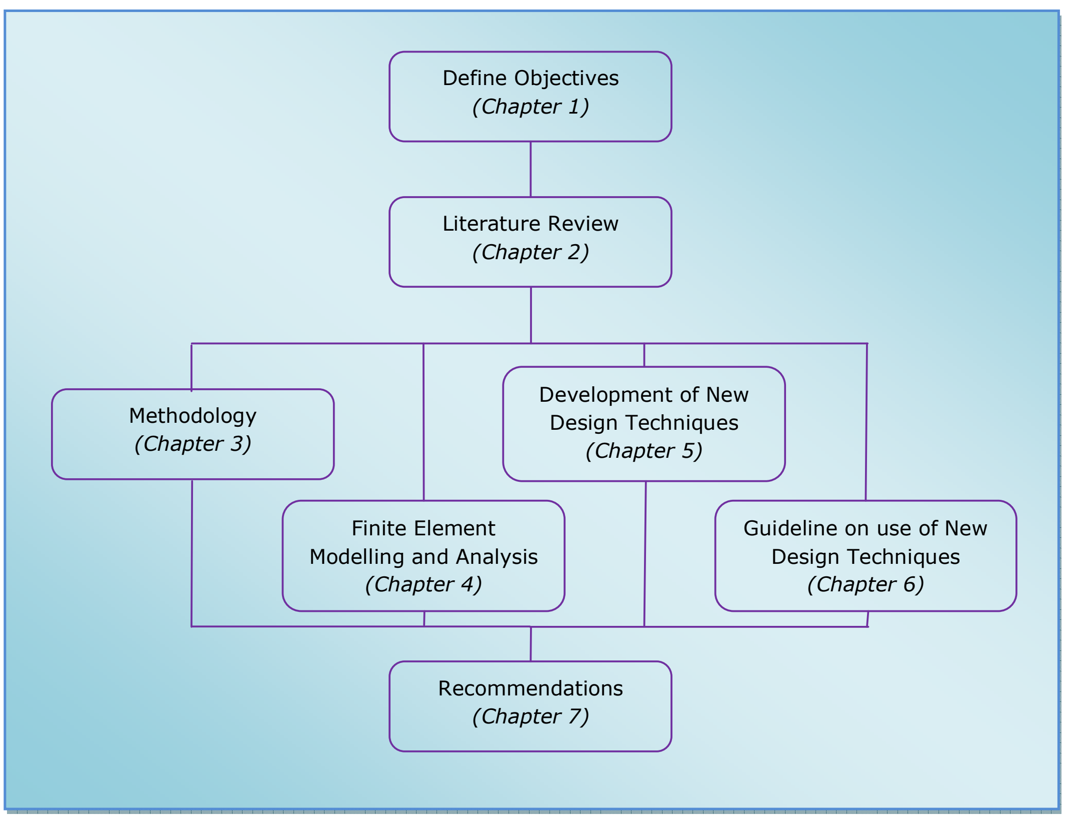

Figure 1.1.1: Simplified Framework for the Study

1.2 Expositions on the Key Aspects

- **<u>Objectives – *Chapter 1*</u>**

This Chapter begins with an introduction of the thesis through a simplified structural framework (Fig. 1.1.1) followed by expounding on those Key Aspects covered inside the respective chapters.

Chapter 1 provides some background on the usual way of designing a deep foundation structure by considering the entire loads being resisted only by the piles to the discussion of using both raft and pile elements which is increasingly gaining recognition in the recent years. It then touches on some problems facing today's engineers in this fast moving world that led to the evolution of this research objectives.

- **<u>Literature Review – *Chapter 2*</u>**

Theoretical studies and researches on related literature are carried out on the undrained soil conditions together with explorations on the geology of Singapore.

The purpose of this literature review are to :

- establish a theoretical framework for the study;
- define key terms, definitions and terminologies;
- facilitate to identify studies, models, case studies to support the research work;
- support to define and establish the areas of the research topic;
- evaluate to ascertain the developed design charts and design table.

Three key points of this literature review are to :-

- provide evidences on the substantive findings done (theory);
- provide ideas on how the research is carried out (methodology);
- reflect what is missing, i.e. the gap that this research could fill.

- **Raft Foundation – *Chapter 3 to Chapter 6***

The research work places great emphasis on the study of the bearing capacity of the raft foundation against settlement behaviours in an undrained soil condition.

A wide range of square raft foundation models are loaded with uniformly distributed loads on the raft with different sizes (5m x 5m, 10m x 10m, 20m x 20m denoted as small, medium and large foundations respectively) and thicknesses together with different types of soil parameters adopted, computed and analysed during the studies. A design chart on short-term bearing capacity against settlement is established and developed (Fig. 4.2.4). Evaluation on this newly developed design chart could best be done by comparing it with numerical results which are prepared and presented in this study. Self-explanatory methodology flowchart reflecting the proposed design pedagogy of the raft foundation is established together with guided procedure steps and some worked examples for learning and practice purpose.

- **Piled-Raft Foundation – *Chapter 3 to Chapter 6***

The research work encompasses investigation study on bearing capacity of piled-raft foundation behaviours in an undrained soil condition.

Laden with uniformly distributed load, the piled-raft foundation with different sizes (5m x 5m, 10m x 10m, 20m x 20m denoted as small, medium and large foundations respectively) are modelled with different arrangement of piles, length of piles and spacing of piles with a variety of soil parameters similar to the raft foundation. This would allow vis-a-vis comparison to be made between same sizes of raft and piled-raft foundations to study any significance contribution from the raft element i.e. degrees of efficiency and behaviours.

A short-term bearing capacity of these piled-raft foundations against settlement design charts are established and developed (Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5 respectively); providing wide spectrums of bearing capacity. Evaluations on these newly developed design charts are done by comparing with some elastic solutions which are prepared and presented in this study. Self-explanatory workflows reflecting the proposed design pedagogies of these piled-raft foundations have been established together with guided systematic procedures and some worked examples for learning and practice purpose.

- **Conclusion – *Chapter 7***

All findings on both raft and piled-raft foundations are consolidated, integrated and presented in this chapter.

The ultimatum objectives are the evolution of the simplified design charts and design table on short term (raft or/and pile) bearing capacities of a foundation to provide a quick and preliminary design.

Self-explanatory workflows reflecting the proposed design pedagogies of the foundations have also been established together step-by-step procedures with some worked examples.

1.3 Background

The thesis shall serve as a fully compiled report on this research work.

In a foundation design, it is normal to consider the use of a shallow or raft foundation to support a structure, and if this is not adequate, then it is required to design a pile-supported foundation. It is usual for a raft to be a part of the foundation system. In recent years, there has been an increased recognition that the strategic use of piles could reduce the total and differential settlements of the raft, and this can lead to considerable economy without compromising the safety and performance of the foundation. Such a foundation makes use of both the raft and the piles, and is referred to here as piled-raft foundation by *Poulos (2000).*

One of the main difficulties confronting today's project personnel – engineers, managers, quantity surveyors or even safety officers and risk assessors on concerning the deployment of raft or piled-raft foundation scheme at almost instantaneously is the availability or access to permit quick prediction of immediate or short-term differential settlement information. In a modest attempt to alleviate these difficulties, one of the objectives for this research work is to produce some simplified design techniques to calculate the bearing capacity of a foundation (raft or/and pile) to allow users to have a quick preliminary design guide.

Three-dimensional FEM geotechnical software is used in the analyses and computation works to help model these foundations under the influence of soil-structure interaction (Fig. 1.3.1) to generate and establish short-term bearing capacity of foundation. Elastic study are used to evaluate these results obtained from the computation work.

The studies included some newly developed simplified design techniques highlighting significant contribution from the raft in piled-raft foundation. Design pedagogies with self-explanatory flowcharts, systematic procedures and some worked examples are produced for completeness.

Finally yet importantly, every effort has been made to ensure the presentation of this thesis is rational and reasonable. Where appropriate, references are also made on earlier research work done by others to support this thesis.

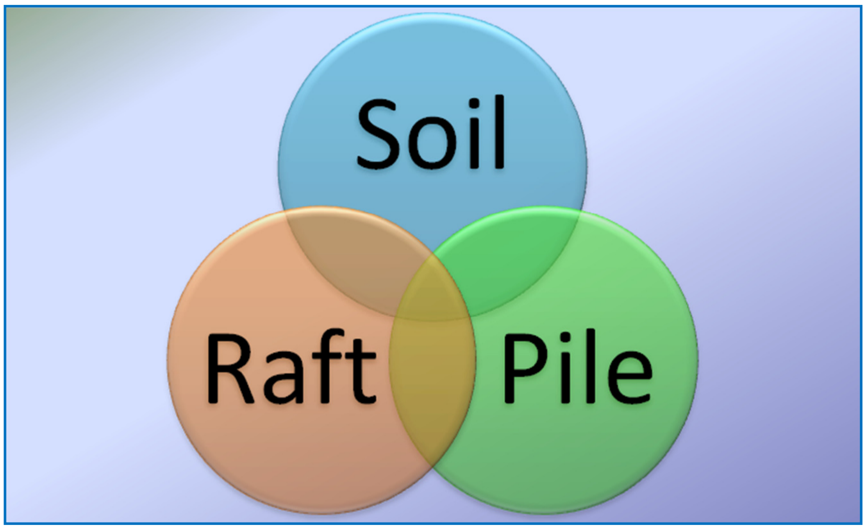

Figure 1.3.1: Framework on Piled-Raft-Soil Interaction Relationship

1.4 Problem Definition

The purpose for having this section in the report is to provide some information on the existing problems facing the engineers, developers and constructors when doing design submission for approval on foundation for a structure design. In addition, these problems helped to evolve the objectives of this research study.

In Singapore, it is a statutory requirement to ensure that all design submissions on the foundation work must include allowable settlement not exceeding up to 25mm in undrained soil condition e.g. *BCA (Building and Construction Authority) & LTA (Land Transport Authority) Design Criteria*.

In order to develop some raft and piled-raft design techniques permitting optimal control of the displacement, range of raft sizes with various thicknesses, number of piles, length of piles and spacing of piles among other soil parameters are identified and executed in the numerical analyses.

Numerous piled-raft models are loaded with uniformly distributed load on the soft clayey soil overlying a layer of firmer clayey soil. Short-term total vertical settlements of up to 25mm against bearing capacity, which is converted into total permissible loads (dead & imposed), design charts for undrained shear strength of soils (10kPa, 20kPa, 30kPa & 40kPa) are established with results been investigated and evaluated. These newly developed design techniques allow users to choose a desirable foundation size based on their need or constraint (e.g. physically or geographically) quickly during the preliminary design stage or when planning for a new project.

Generally, both total settlements in short-term or long-term by itself are rarely damaging. However, differential settlement is, but it may be reduced through prudent design. Most buildings can tolerate 20mm differential settlement, and because differential settlements are unlikely to exceed 75% of average total settlements, thus a maximum settlement of around 25mm are normally use as a safe guide for buildings as highlighted by *Terzaghi & Peck (1948).*

1.5 Objectives

The objectives of this research are to:-

a) Investigate the undrained bearing capacity and vertical settlement behaviours of raft and piled-raft in the soft clay using 3-D finite element analyses;

b) Compute the bearing capacity contribution by the raft through various simulation from the loaded piled-raft models;

c) Develop simplified design techniques to permit a quick preliminary assessment and design of raft and piled-raft foundation for project planning & cost estimation purpose, and safety and risk analysis study;

d) Develop design pedagogies, self-explanatory design workflows, step-by-step procedures together with some worked examples on the raft and piled-raft foundations design to allow learning and practice.

1.6 Summary

In brief, Chapter 1 presents the necessary background information that have been considered and applied in this research project. It outlines the specifications of the research work, scopes and areas of interest, it also provides guidance on defined problems together with the approaches and methodologies used to explore on the identified objectives for this research work.

Simplified framework of this research work is best explained through illustration reflected in Figure 1.1.1. Seven chapters are presented to cover the entire presentation of this research study, all the details and facts are methodically reported and properly accounted in their respective chapters.

CHAPTER 2

LITERATUERE REVIEW

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This literature review examines the existing literature to discover the strengths and weaknesses in the read literature. As well as demonstrating knowledge of existing research, the literature review also identifies gaps that this thesis as a whole is intended to fill. In summary, it provides the background to, and reasons for, conducting this research.

PART I: INTRODUCTION ON COHESIVE SOIL

2.2 The Nature of Soil

There are some reasons causing displacement of soils. In general, soil is a non-homogeneous porous material consisting of three phases: solid, fluid (normally water), and air (Fig. 2.2.1). Any changes in stress, water content, soil mass, or temperature would cause some deformation to the soil structure. The stresses in the soil could occur from soil weight, surface loads, and environmental factors such as desiccation from drought, wetting from rainfall, and changes in depth to groundwater in the soil profile.

Cohesive soil often contains fine-grained materials consisting of silt, clay, and organic material. These soils have significant strength when in confined and air-dried. Most cohesive soil is relatively impermeable, and when loaded it deforms in a manner similar to gelatine or rubber, i.e. the undrained state.

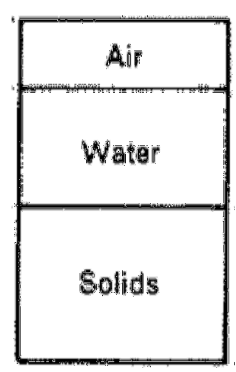

Figure 2.2.1: Components of Soil

(Source from Craig, R.F., 1992)

PART II: GEOLOGY OF SINGAPORE

2.3 Geology of Singapore

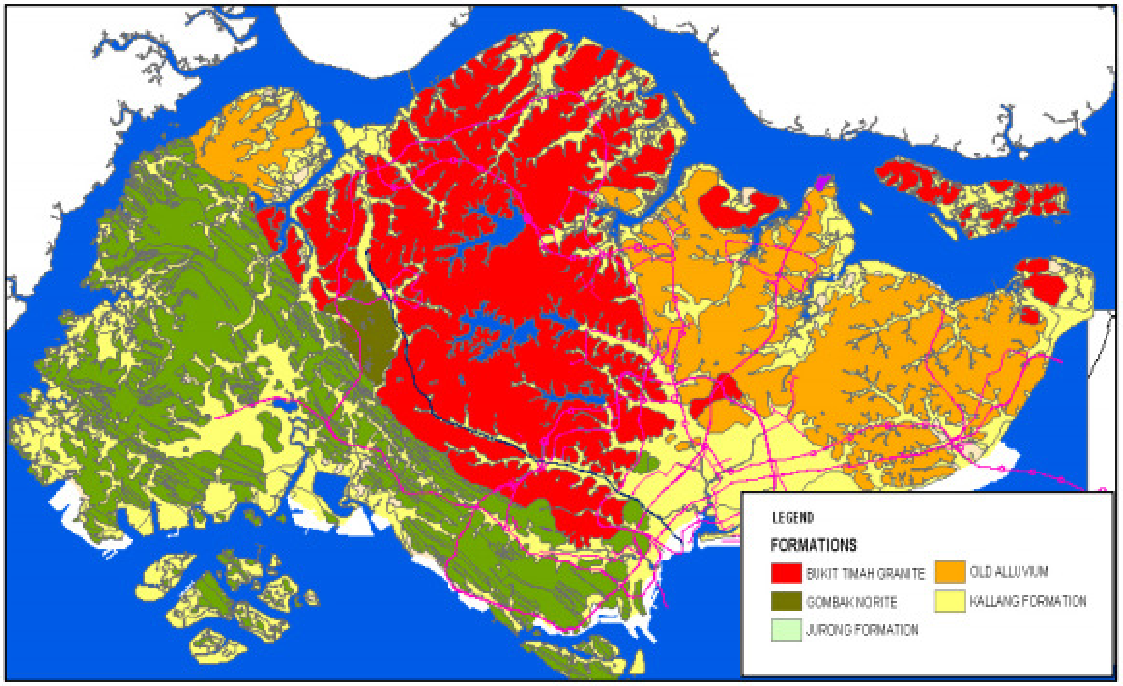

Figure 2.3.1: Geology of Singapore
(Source from World Tunnel Congress, 2008)

Singapore is a small island stretches slightly over an area of 720 km^2 that includes the offshore islands. Locating near to the Equator and in the South East Asia region, the climate is usually hot and humid with an annual rainfall ranging from 1600mm in the southwest to 2500mm in the central regions. Despite small in size, it contains a wide range of variable and rapidly changing geology, making the ground conditions difficult to predict. Figure 2.3.1 shows a simplified map on Geological of Singapore.

Based on these local conditions, the rocks are deeply weathered. Hence, various types of sub-soils could be found, and they range from very soft peat and marine clay in the low-lying areas to hard rock such as sandstone and granite. There are five formations classified for Geology of Singapore and are shown in Figure 2.3.1.

The first four are the main formations of Singapore's geology. However the first two formations, Kallang and Jurong formations, post numerous problems to engineer with regard to the construction of foundations and substructures.

This geology, combined with the urbanisation of the island, further highlights the importance of settlement control to all construction projects in Singapore.

2.4 Kallang Formation

A subset of Old Alluvium, "Kallang Formation" is a soft soil found as topsoil in areas of the Old Alluvium. Kallang Formation usually contains materials with soft marine clay and loose alluvial muddy sand usually found in all river valleys and mouths.

The reason for this formation to be named as Kallang is probably due to the existence of the Kallang river basin where it is the most extensive previously, and is found along the coastline and extends into the headwaters of the rivers draining Singapore. Most of the evidences for the existence and subdivision of this formation comes from boreholes and the physiographic settings of the deposits. Five members are recognised within the formation, and these are referred to informally as:

i. Marine Member – soft grey clay deposited offshore;

ii. Alluvial Member – loose muddy sand and sand deposited in river valleys;

iii. Littoral Member – loose muddy sand and sand with shells deposited on coastal beaches;

iv. Transitional Member – soft dark grey organic/peat clay and clayey peat deposited in mangrove areas;

v. Reef Member – loose calcareous sand and corals formed offshore.

In addition, most of the soft clay found in Singapore belongs to the Marine Member, which appears in two layers, the upper and lower marine clay , separated by a thin layer of stiff clay. The soil is normally consolidated with average shear strength of $10kN/m^2$ to $40kN/m^2$ respectively.

Generally, the thickness of Kallang Formation is up to 20m near the estuaries, but the depth varies when it is found at the Rochor and Changi areas, the thickness could be as deep as 40m.

2.5 Old Alluvium

The Old Alluvium, which is generally clayey soil, normally lies on the north-eastern and north-western parts of Singapore.

The old alluvium is a type of alluvial soil that has been in the area long enough to start to compact, however, the term Old Alluvium in Singapore also refers to a specific location and formation. The materials usually contains dense to cemented muddy sand/gravel with beds of silt and/or clay.

2.6 Simulated Soil Condition in This Research

In this research, the basic value of the thickness of the soft clay layer is taken to be 40m underlying another layer of 20m thick firm clay generalize and simulate the problematic soil conditions in Singapore (Para 2.4).

Geotechnical engineering software, 3D Plaxis Foundation, is used to setup the models, analyses and generate the numerical results. Volumetric pile is selected over embedded pile which is a beam element and a simplification of the volumetric pile. Hence, all piles are discretised with volume elements, and interface shear strength reduction factor of soil is applied to simulate the intensely shearing zone in contact with these piles and raft.

The Mohr-Coulomb soil model, which is first-order approximation of soil behavior, is adopted in all analysis. The soil-structure friction strength reduction factor at interface with value of 0.67, which is commonly adopted for cohesive soil at undrained condition, is used from the typical values ranged from 0.6 to 1.0 depending on the type of soils.

2.7 Evaluation of Immediate Settlement Computation Results

Outlines

Computation results from the rigorous finite element modelling using three-dimensional Plaxis geotechnical engineering software are evaluated by :-

i. Existing equivalent raft method [$S_i = (qB/E)\mu_0\mu_1$];

ii. General formula (Equation 7.2.1) to suit the research work.

General

Elastic or immediate deformation caused by static loads is usually small, and it occurs essentially at the same time these loads are applied to the soil. Elastic theory have been found to be useful for the evaluation of immediate settlement when cohesive soil is subjected to moderate stress increments. The immediate settlement of a structure on cohesive soil consists of elastic distortion associated with a change in shape without volume change, which is caused by the elastic deformation of dry soil, partially saturated soil and saturated soil. The theory of elasticity is generally applicable to cohesive soil; *Chrisrian and Carrier, method of determining settlement under an undrained condition (1978).* The average immediate settlement of a foundation on an elastic soil may be given by :

Si = (qB/E)$\mu_0\mu_1$

where μ_0= influence factor for depth *D* of foundation below ground surface, μ_1 = influence factor for foundation shape and *E* = equivalent Young's Modules of the soil. However, this formula has its limitations as follows:

- does not take into consideration of the raft's contribution;
- does not take into consideration on the orientation of the piles and spacing.

A uniform pressure applied to a rigid foundation on cohesive soil could cause the soil contact pressure to be maximised at the edge and decreases towards the centre. This is due to additional contact pressure which is generated to provide stress that shears the soil around perimeter (Fig. 2.7.1). Whereas a uniform pressure applied to a flexible foundation on cohesive soil causes greater settlement near the centre than the edges because the cumulative stresses are greater near the centre, as a results of the pressure bulb stress distribution (Fig. 2.7.2).

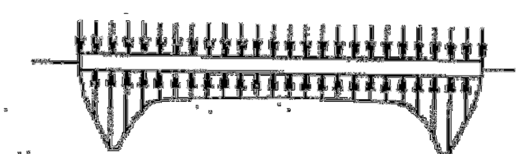

Figure 2.7.1: Rigid Mat on Cohesive Soil

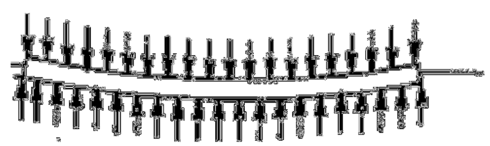

Figure 2.7.2: Flexible Mat on Cohesive Soil

Pressure bulb is a common term that represents the volume of soil or zone below a foundation within which the foundation loads induces appreciable stress. The stress level at a particular point of soil beneath a foundation may be estimated by the theory of elasticity (Fig. 2.7.3).

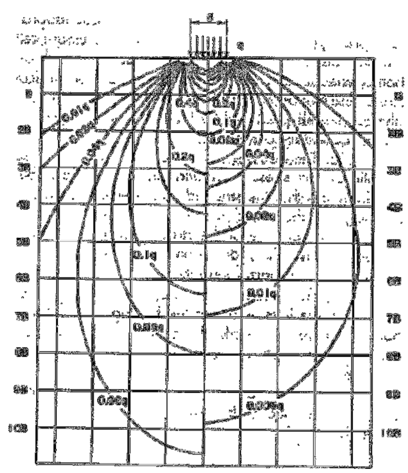

Figure 2.7.3: Pressure Bulb of Stressed Soil

(All three sources from US Army Corps of Engineers, No 9, Settlement Analysis)

PART III: TYPES OF FOUNDATION DESIGNS

2.8 General

A pile foundation is designed to transfer all the loads from the structure to the earth for support.

They could broadly be classified into two types; shallow or deep foundation. Shallow foundations are used for the raft section, and deep foundations for the piled-raft section. These structures could have behaved as rigid or flexible foundation (Fig. 2.7.1 and Fig. 2.7.2).

Flexibilities of the foundation are determined on it settlement behaviour. The shape of the deformation pattern varies, depending on the flexibility of the foundation and types of soil. Figure 2.7.3 illustrates the relative distribution of soils contact pressure and displacements on cohesive soil with linear contact pressure distributions from uniformly applied pressure *(q)* are often assumed for settlement analysis.

2.9 Shallow Raft Foundation

Generally, a foundation is considered shallow when it is embedded with depth less than the width of the raft. The structure transfers forces to the earth near the surface, in other words, shallow foundation is located below the lowest part of the superstructures. Normally, there are two types of support, footing or raft foundation.

The meaning of footing is simply an enlargement slab to support the column or wall. Hence, the meaning of raft foundation is having a number of columns or rows of walls been supported by a slab structure.

2.10 Deep Raft Foundation

Generally, a deep foundation is different from shallow foundation by the depth, in other words, deep foundation is embedded down into the earth. Therefore, the situation of using deep foundation is when a shallow foundation is deemed inappropriate i.e. when subject to bearing capacity failure and/or excessive settlement in poor quality soil. Materials for the foundation could be made from timber, steel, reinforced concrete and pre-tensioned concrete. In addition, deep foundations could be installed by either driving them into the ground or drilling a shaft and filling it with concrete, mass or reinforced.

2.11 Rigid Raft Foundation

This is the simplest approach. It assumes that mat is infinitely rigid with negligible flexural deflection and the soil is a linear elastic material (Fig. 2.7.1). It also assumes the soil bearing pressure is uniform across the bottom of the footing if only concentric axial loads are present, it varies linearly across the footing if eccentric, or moment loads are present.

2.12 Flexible Raft Foundation

It is assumed that the loaded mat foundation is founded on a bed of springs to simulate the flexible behaviour (Fig. 2.7.2). Attention is required when selecting the modulus of subgrade reaction as it depends on many factors like the width and shape of the mat. The actual behaviour is that settlement in the centre is higher than that at side edges. Consequently, it leads to an underestimation of bending moment by 18% to 25% as suggested by *Donald, P. C. (1994).*

PART IV: FOUNDATION DESIGN PHILOSOPHY

2.13 History on Conventional Design of Piled-Raft Foundation

Foundation design in soft clay for a large structure such as storage tank, blast furnace and low-rise to medium-rise building founded on raft foundation may have an adequate factor of safety against ultimate bearing capacity, but the settlements may be excessive and unacceptable. Normal engineering practice will then be to introduce piles in order to reduce the settlements of the raft. In cases where raft itself does not provide adequate bearing capacity, then the addition of piles is also use to improve the factor of safety against ultimate bearing capacity. This combined foundation system is often referred to as the pile-raft foundation.

The piled-raft is a foundation system consisting of three elements, i.e. piles, raft and soil. The full detailed analysis of a piled-raft is not trivial due to its three-dimensional nature and the complicated interactions among piles, soil and raft. The conventional design of piled-rafts often conservatively ignores the contribution from the raft, and assumes that the piles carry all the imposed loads. The usual practice is to choose the number of piles in order to give an adequate factor of safety against individual pile failure, without taking into account the contribution of raft to the total bearing capacity. As a result, the conventional piled-raft designs are often conservative. The overall settlement of piled-raft in such conventional designs is often very small, owing to the installation of longer or more piles than are necessary. Obviously, solutions that are more economical could be obtained by accounting for the contribution of the raft.

2.14 Conservative Design of Piles in Pile Foundation

The use of pile as settlement reducer is effective for controlling the total and differential settlements of a raft that already has an adequate bearing capacity. In this way, much smaller number of piles than that calculated by conventional design methods is often adequate for reducing the raft settlement to an acceptable limit. In conventional piled-raft foundation design, the number of piles is normally large and the load carried by each individual pile is relatively small. There is a high safety margin before the piles reach their ultimate geotechnical bearing capacity or structural failure load. The capacity of the piles is governed by geotechnical considerations rather than by the compressive strength of the pile material as highlighted by *Wong and Chang et. al. (2000).*

Current practice in piled-raft foundation design treats the raft as a large pile cap. In order to ensure that the pile could perform satisfactorily, it is necessary to provide the piles with an adequate safety factor against bearing resistance failure. In traditional geotechnical practice, a global safety factor is applied directly to the calculated ultimate geotechnical capacity of a pile to arrive at its allowable capacity.

In Singapore, the subsoil conditions may vary significantly over short distances and this usually pose some challenges to the road engineers when preparing stratigraphy drawing for the Geotechnical Baseline Report since the percentage of the accuracy of the soil profile depends very much on the proximity between boreholes executed. Thus, this could easily explain why designers usually tend to be more conservative when doing pile foundation design to compensate for any unforeseen ground conditions between boring points.

In terms of spacing between points of exploration during ground investigation, the relevant guidelines contained in BS5953:1999 Code of Practice for Site Investigations, Clause 12.6 stated that "Although no hard and fast rules can be laid down, a relatively close spacing between points of exploration, e.g. 10m to 30m, are often appropriate for building structures. For building structures smaller in plan area, exploration should be made at minimum of three points, unless other reliable information is available at the immediate vicinity." In addition, BCA's Advisory Note specified to having minimum of one boring for every 300m^2 areas to be prepared.

2.15 New Design Philosophy

In the new design philosophy, the raft is often designed to resist major mass from the foundation loads, and piles are designed as settlement reducers, which are employed mostly to limit otherwise excessive average and/or differential settlements, rather than to carry the entire foundation loads. In this new design philosophy, the ultimate geotechnical bearing capacity of the piles could be fully utilised at the design-working load. This is acceptable if the piles are not required from a bearing capacity point of view, but merely as settlement limiters.

Although *Burland et. al. (1977)* mooted the concept of settlement reducing piles, its recognition is novel and research attention is only gradually given over the past decade, e.g. *Randolph (1994), Burland (1995), Poulos (2001a), Love (2003),* etc.

2.16 Classification of Available Methods of Analysis

Poulos et. al. (1997) classified the various methods of analysing piled-rafts into the following three broad classes:

- Simplified calculation methods;
- Approximate computer-based method; and
- Rigorous computer-based method

The following present a brief description on various methods of analysis summarized by *Poulos et. al. (1997) and Poulos (2001b).*

(a) Simplified calculation methods involve a number of simplifications in relation to the modelling of the soil behaviours and soil-structure interactions. Simplified methods include:

- Method employing the concept of interaction factors and the principle of superposition, e.g. *Poulos and Davis (1980);*
- Settlement ratio methods, in which the settlement of a single pile at the average load level is multiplied by a group settlement ratio, which reflects the effects of group interaction, e.g. *Fleming et. al. (1992);*
- Equivalent raft method, in which the pile group is represented by an equivalent raft acting at a characteristic depth along the piles depending on the soil types, e.g. *Tomlinson (1986);*
- Equivalent pier method, in which the pile group is represented by a pier containing the piles and soil between them. The pier is treated as a single pile of equivalent stiffness in order to compute the average settlement of the group, e.g. *Poulos and Davis (1980).*

(b) Approximate computer-based methods include the following:

- Method employing a "strip on springs" approach, in which the raft is represented by a series of strip footings, and the piles are represented by springs of appropriate stiffness, e.g. *Poulos (1991);*
- Method employing a "plate on springs" approach, in which the raft is represented by a plate and the piles as springs, e.g. *Clancy and Randolph (1993) and Poulos (1994).*

(c) Rigorous computer-based methods include:

- Boundary element methods, in which both the raft and piles within the system are discretised, is made of elastic theory, e.g. *Butterfield and Banerjee (1971), Kuwabara (1989) and Sinha (1997);*
- Methods combining boundary element for the piles and finite element analysis for the raft, e.g. *Hain and Lee (1978), Ta and Small (1996), and Franke et. al. (1994);*
- Finite difference analyses via the commercial programs FLAC e.g. *Lin and Feng (2006),* FLAC3D *e.g. Poulos (2001b), Gopinath et al (2010), Adel et. al. (2014);*
- Simplified finite element analyses, usually involving the representation of the foundation system as a plane strain problem e.g. *Desai (1974),* or an axisymmetric problem e.g. *Hooper (1974);*
- Three-dimensional finite element analyses, e.g. *Wang (1996)* and *Katzenbach et. al. (1998).*

(d) *Poulos (2001b)* performed a comparison of some of these methods made for a very simple idealized problem. Some of the conclusions drawn from the comparison are:

- Simple methods could be used with some confidence for preliminary design purposes, with the more complex analyses being left for the detailed design stage;
- Three-dimensional analyses are potentially the most accurate numerical methods available for piled-raft foundation analysis, although they are very time-consuming to set up and run.

2.17 3-D Finite Element Modelling

Owing to its ability to simulate geometry variation, material heterogeneity and non-linearity, construction sequence and time-dependent consolidation phenomenon, three-dimensional (3-D) finite element modelling allows more realistic and comprehensive studies of geotechnical engineering problems. However, a 3-D finite element analysis of a static equilibrium problem in engineering often requires the solution of very large equation systems, typically of the order of tens or even hundreds of thousand, to maintain reasonable realism and accuracy. This often leads to two main numerical difficulties, i.e. the enormous storage requirements (for coefficient matrix and working activities) and unacceptably long computational time. Immense and expensive computer resources, e.g. central processing unit (CPU), input and output (I/O) devices, random access memory (RAM), disk capacity, etc. are therefore required.

As a result of the rapid development and readily availability of high-speed digital computers, 3-D finite element analyses are now increasingly conducted as part of the design process or back-analysis to better understand ground mechanisms and soil-structure interactions e.g. *Lee et. al. (1995); Chan et. al. (2003).* To date, some full 3-D finite element modelling of piled-raft foundations have been reported, including *Wang (1996); Katzenbach et. al. (1998); Reul and Randolph (2003); Reul (2004); Katzenbach et. al. (2005); Sanctis and Mandolini (2006); Poulos and Bunce (2008).* However, very little attention has been on the bearing and settlement behaviours of raft and piled-raft foundations in soft clay.

2.18 Choices of the Constitutive Models in Consideration

There are two constitutive models for consideration to be adopted for use in this entire research analysis work.

i. The elastic-plastic Mohr-Coulomb model involves five input parameters; E and v for soil elasticity, φ and c for soil plasticity and Ψ as an angle of dilatancy. This Mohr-Coulomb model represents a "first-order" approximation of soil or rock behaviour, it is recommended to use this model for a first analysis of the problem considered. For each layer, one estimates a constant average stiffness. Due to this constant stiffness, computations tend to be tentatively fast and one obtains a first impression of deformations. Besides the five model parameters mentioned-above, initial soil conditions play an essential role in most soil deformation problems;

ii. The Hardening-Soil model is an advanced model for the simulation of soil behaviour. As for the Mohr-Coulomb model, limiting states of stress are described by means of the friction angle, φ, the cohesion, c, and the dilatancy angle, Ψ. However, soil stiffness is described much more accurately by using three different input stiffness: the triaxial loading stiffness, E_{50}, the triaxial unloading stiffness, E_{ur}, and the oedometer loading stiffness, E_{oed}. As average values for various soil types, we have $E_{ur} \approx 3E_{50}$ and $E_{oed} \approx E_{50}$, but both very soft and very stiff solid tend to give other ratios of E_{oed}/E_{50}.

In contrast to the Mohr-Coulomb model, the Hardening-Soil model also accounts for stress-dependency of stiffness moduli. This means that all stiffness increase with pressure. Hence, all three input stiffness relate to a reference stress, being usually taken as 100kPa (1 bar).

2.19 Adoption of Constitutive Soil Model – Mohr Coulomb Model

Mohr-Coulomb model, a well-established theory, is adopted in this entire research work. It is a “first-order” approximation of soil behaviour and an elastic-perfectly plastic model that is often used to model soil deformation and failure.

More often than not, types of geoengineering analysis work are broadly divided into the following two groups:

b) those whose goal is to assess bearing capacity and slope of wall stability which are related to the ultimate limit state analysis (ULS);

c) those which are related to the serviceability limit state analysis (SLS), such as deep excavations or tunnel excavations in urban areas.

2.20 Most Used Methods of Calculating Immediate Settlement

Immediate settlement is generally considered the settlement that takes place under constant volume (undrained) conditions when the clay deforms to accommodate the imposed shear stresses. The immediate settlement may be calculated using various procedures and those which seem to be of most use in practice have been tabulated below :-

Method	Formula	Reference
Elastic strain summation	$\Sigma[\sigma_z - 0.5(\sigma_x - \sigma_y)]\delta h / E_u$	Davis and Poulos (1968)
Elastic displacement	$[q.B.\ \mu_o.\ \mu_1] / E_u$	Christian & Carrier (1978)
Finite element	By computer	-
Improved formula	$Si = (qB/E)\mu_0\mu_1 * (B_e/B)$	TanKL (2014) - *Refer to Para 7, Equation 7.2.1*

Table 2.20.1: Most Used Methods of Calculating Immediate Settlement

Among all, the elastic displacement set of formula seems to be the most commonly used numerical formula for calculating the immediate settlement due to its simplicity. In the equation, the Poisson's ratio is taken as 0.5. The influence factors μ_o and μ_1 are sensitive to the depth and the length/breadth ratio of the equivalent block foundation, and the thickness of the compressible clay layer. The value of E_u is therefore required and the main difficulty in predicting immediate settlement is in the determination of this parameter. A value of E_u could be determined by means of the undrained triaxial test (Figure 2.20.1). However, such a value would be very sensitive to sampling disturbance and would be too low if the unconsolidated – undrained tests were used.

Usually, to assume the Young's Modulus, soil would be tested in a conventional triaxial compression device under constant lateral stress to yield a tangent elastic modulus E

equivalent to Young's Modulus. The soil modulus *E* is assumed approximately equal to Young's Modulus in practical applications of the theory of elasticity for computation of settlement.

In principle, the unconsolidated undrained triaxial test enable the undrained strength of the clay in its in-situ condition to be determined, the void ratio of the specimen at the start of the test being unchanged from the in-situ value at the depth of sampling. There are some major advantages and limitations on the use of this triaxial apparatus for soil on unconsolidated undrained condition test as follows:-

<u>Advantages:</u>

- Accurate results due to computer control (in most cases);

- Different types of loading conditions could be tested;

- Many different soil properties could be found (shear strength, internal friction angle etc.);

- Relatively simple preparation and testing procedures;

- Most commonly used soil testing method.

<u>Limitations:</u>

- Basic triaxial apparatus would not take into account changes in area (i.e. as the sample is compressed it's area will increase slightly);

- In practice, the effects of sampling and preparation result in a small increase in void ratio;

- The soil sample has been remoulded (i.e. taken out of ground and been effected by different pressures etc.) and would not exactly match in-situ conditions. So properties found in triaxial test might not exactly match soil properties and dependent on the skills of the tester;

- Although the name triaxial test suggests that the stresses would be different in three directions ($\sigma_1 \neq \sigma_2 \neq \sigma_3$), this is not true in the test as is usually done (Fig. 2.20.2). In this test, oil or water is as confining medium, the confining pressures are equal in all directions (i.e. in terms of principal stresses: for a compression test: $\sigma_1 \neq \sigma_2 = \sigma_3$)

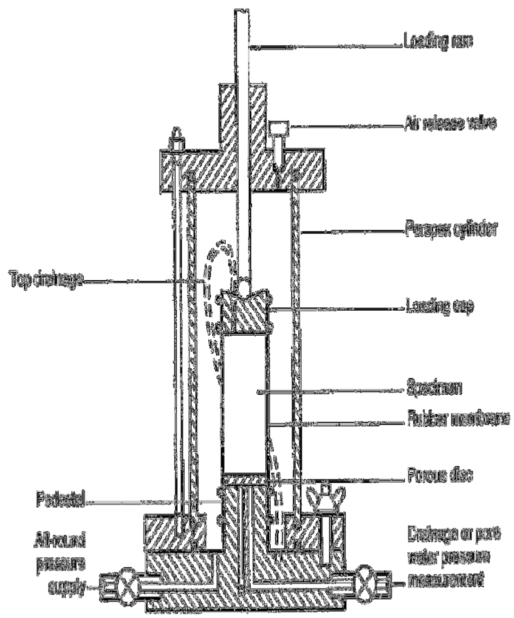

Figure 2.20.1: Triaxial Test Apparatus

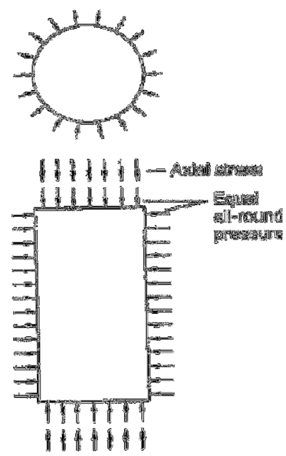

Figure 2.20.2: Stress System

(All two sources from Craig, R.F., 1992)

PART V: BASIC DESIGN CONSIDERATIONS

2.21 Requirements and Guides

Design requirements and guides leading to complete design of foundation structure have been spelled in *BS8004:1986*, the Code of Practice for Foundations. The Code gives presumed bearing values for preliminary design, allowable bearing pressures being generally determined by permissible settlements. Followed by, the ultimate bearing capacities would have to be considered as well, but would be taking the serviceability conditions as the most critical criteria at this stage. Once the size of the base has been determined from serviceability loadings, the raft would then be designed using the ultimate loads. Ultimately, the thickness of the raft must be sufficient to resist the bending moments and shear force at ultimate limit state.

At present, there are considerable evidence on the distress to buildings caused by differential settlements, *Skempton and Macdonald (1956) and Bjerrum (1963).* This indicates that damages are rarely caused by angular distortion in excess of 1:300 and a safe limit for design to prevent the cracking of finishes is 1:500. It could be seen that the structures observed are within this limit, and it is confirmed by the fact that no signs of distress are evident in any of the structures studied.

In Singapore, all foundation design for buildings' submission have to be submitted to the Building & Construction Authority (BCA) to seek for statutory written approval prior to any execution of work on site is legally allowed. One of the main design criteria imposed by the BCA is the allowable settlement of up to 25mm has to be met in the design submission. This design criterion has also been reinforced and practised in other Authority agencies e.g. Land Transport Authority (LTA), Housing and Development Board (HDB), National Park Authority (NPA).

2.22 Factors Influencing Bearing Capacity of Soil

Design Considerations for Raft Foundation

Lin and Feng (2006) on "A Numerical Study of Piled Raft Foundations" had concluded that contact pressure developed in raft-soil interface for a constructed piled-raft could achieve of up to 25% of the total loading. This implied that almost ¼ of the design loading could reduce the loading carried by the pile group. However, designs should be examined further for subsoil conditions, as it tends to cause significant ground settlement. Thus, it would be good to consider pile-raft-soil relationship when doing piled-raft foundation design.

When designing the size of the raft, it may be worth to take note that having larger rafts size might not be necessary producing higher bearing capacity, *De Beer (1965)* has shown that the bearing capacity decreases with an increase in foundation size from some collected experimental data. It is noted that the thickness of raft affects differential settlement and bending moments, but has little effect on load sharing or maximum settlement *(Poulos, 2001).*

Shallow foundations spaced sufficiently closed together to intersect adjacent shear zones may decrease bearing capacity of each foundation. It has suggested that spacing's between footings should be at least 1.5 times the footing's width, to minimize any reduction in bearing capacity. Increases in settlement of existing facilities should also be checked when placing new structure near existing facilities *(Bearing Capacity of Soils by American Society of Civil Engineers).*

Design Considerations for Piled Foundation

Fleming et .al. (1985) reported that the stiffness of the pile cap would influence the distribution of structural loads to the individual piles. It would be good to understand that the raft thickness has little influence on the differential displacement if the piles were placed optimally *(Widjojo, A. and Fred, H. (2001); Prashant et. al. (2013)).*

On distribution of the bearing capacity on a piled foundation, *Widjojo, A. and Fred, H. (2001)* reported for deep piles, the tip resistance was smaller compared with the side resistance and generally, a raft and piled-raft foundations' typical displacement profiled downward dish shape or saddled-shape. Excerpt from *Bearing Capacity of Soils by American Society of Civil Engineers* also highlighted that skin friction on often contributes the most bearing capacity in practical situations unless the base is bearing on stiff shale or rock that is much stiffer and stronger than the overlaying soil from.

Some studies have been done on having longer pile length against having more closely spaced piles. *Vipman (1999)* has highlighted that the effect of increasing the length of the pile is the general reduction in the maximum displacement, differential displacement and bending moment. The percentages of total load taken by the piles increase with the increased length of these piles *(Seyed et. al., 2014).* The effect of increasing spacing between the piles is a general increase in the maximum displacement, differential displacement and bending moment. In summary, closer spacing of piles helped to reduce the differential settlements.

In general, total pile capacity is the summation of skin friction together with the end bearing. The amount of end bearing and skin friction mobilized depends on pile settlement and condition of the soil. Usually, the resistance from the skin friction is higher than the tip during short-term settlement period (Fig. 2.22.1).

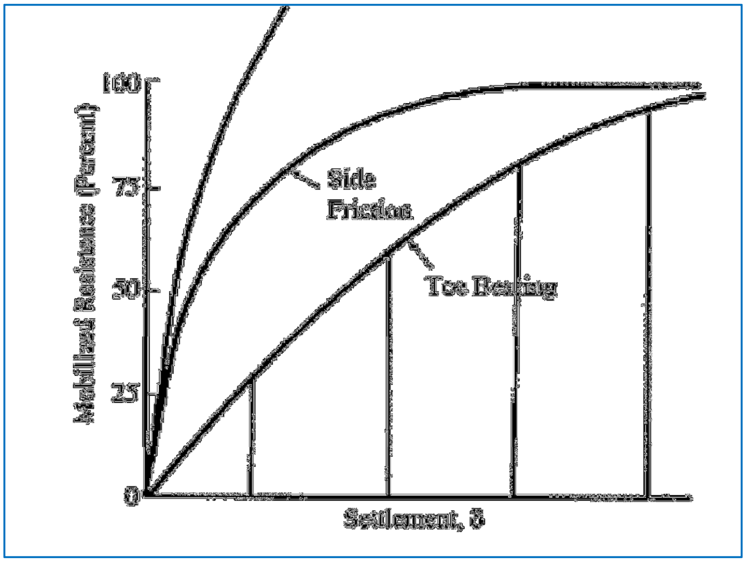

Figure 2.22.1: Load-Displacement Response
(Source from Fellenius, 1999)

When designing space between piles, *Vesic (1977)* suggested that piles in a group should be spaced so that the bearing capacity of the group is optimum. The optimum spacing for driven piles is 3 to 3.5 pile-widths. In addition, as mentioned in the Reinforced Concrete Design 4th edition book by *Mosley, W.H and Bungey, J.H,* the minimum spacing of piles, centre to centre, should not be less than (1) the pile perimeter for friction piles, or (2) twice the least width of the pile for end bearing piles.

PART VI: LIMITATIONS

2.23 General

A number of comprehensive reports have been published on the use of piles as settlement reducers *e.g. Burland and Kalra (1986); Randolph 1994; Russo and Viggiani (1998); Viggiani (2001); Poulos (2001); Sanctis et. al. (2002); Mandolini et. al. (2005), Hansbo and Kallstrom (1983); Burland and Kalra (1986); Katzenbach et. al. (2000), Russo et. al. (2004).* Less attention has been paid to the bearing capacity of piled-rafts, leaving the old concepts of block failure, originally introduced by *Terzaghi and Peck (1948)*, practically unchanged.

After reviewing the available knowledge on the settlement and bearing capacity of piled-raft foundation, it is noted that an approach to these load-settlement studies is not yet well developed. There are no simplified design techniques for reference:-

- Design charts or table to determine the bearing capacities of both raft and piled-raft foundations at 25mm settlement developed through rigorous 3-D finite element modelling, together with design pedagogies and worked examples,

PART VII: SENSITIVITY STUDIES ON BOUNDARY EFFECT

2.24 General

In this section, the works involved the studies of the sensitivity of the boundary conditions imposed on a series of foundation models.

In reality, it is a common practice to consider having the soil boundary width to be three to five times the dimension of the raft. Some literature even adopted as minimum as double the dimension of the raft *(Ningombam and Baleshwar, 2008)*.

As such, range of a selected 5m x5m piled-raft models with two to four times the width of the raft are adopted as the boundary limits to study the impact on the behaviour of the foundations and their results. Three models (named *A, B & C*) are created with boundary width two, three and four times the width of the raft respectively. All the three models are modelled with same conditions and parameters.

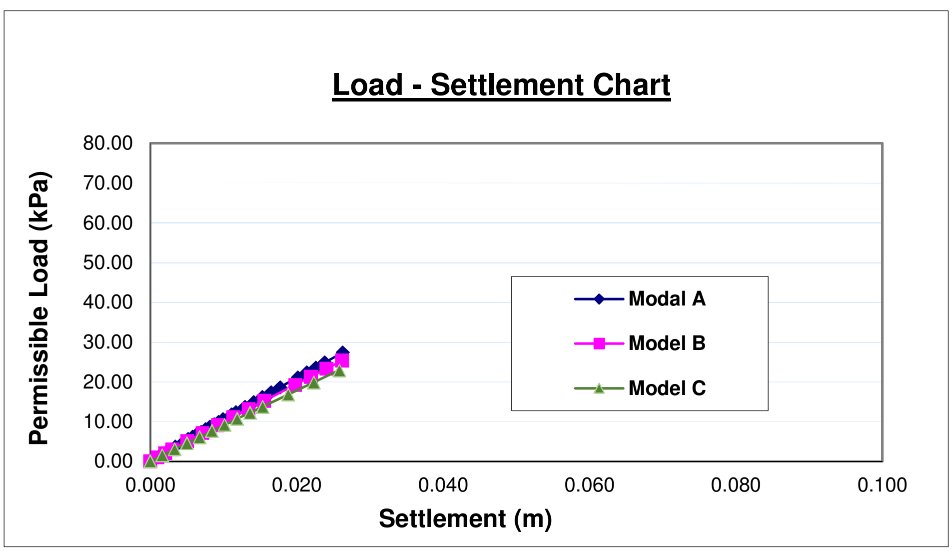

Figure 2.24.1: Sensitivity Studies on Boundary Effect

In general, Model C having the most remote boundary condition considered, so as not to restrict or restraint any movements, has taken the shortest time to complete the analysis, which are then followed by Model B and Model A respectively.

Figure 2.24.1 show all results of the three models (bearing capacity of the soil against maximum settlement) revealing that they are closed with marginal difference. The differences between these three models are observed to be very minimal at 25mm settlement which provide a good platform for the development of simplified design techniques for preliminary design use.

Hence, Model B producing average results is selected to provide proper restraint on the mesh. The boundary conditions used in this study are proposed as follows:

- horizontal boundary to be three times the raft's width measured from the model symmetrical axis;
- vertical boundary to be until the bottom of the stiff clay. That is sixty metre below the ground surface.

PART VIII: METHODS OF DEVELOPING THE SIMPLIFIED DESIGN TECHNIQUES AND EVALUATION WORKS

2.25 Method to Develop the Simplified Design Techniques

First, numerical results from a series of the raft foundation models are studied and developed into a raft foundation design chart (Fig. 4.2.4) with range of information e.g. bearing capacity against settlement, shear strength of soils and size of raft.

Next, numerical results from a series of piled-raft foundation models are studied and developed into series of piled-raft foundation design charts (Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5) with range of information e.g. bearing capacity against settlement, shear strength of soils, length of piles, number of piles, spacing of piles and size of raft. The parameters adopted are similar to the raft foundation models done earlier to allow comparisons to be made.

Finally, both the raft and piled-raft foundation design charts are then consolidated for further study to integrate and to convert them into a versatile Design Table (Table 7.2.1) that comes collectively with the efficiency of the raft's contribution from the piled-raft foundation.

2.26 Methods to Evaluate the Developed Simplified Design Techniques

The developed simplified design techniques mentioned in Para 2.23 are evaluated with theoretical calculations using the existing equivalent raft method, since the elastic theory has been found to be useful for evaluation of immediate settlement for cohesive soil condition.

To demonstrate the reliability, repeatability and usability of these developed simplified design techniques (Para 2.23), results generated from these developed simplified design techniques are compared with two similar references found in recent published international journal and conference.

CHAPTER 3

METHODOLOGY

CHAPTER 3: METHODOLOGY

3.1 Range of Parameters Considered for Raft Foundation

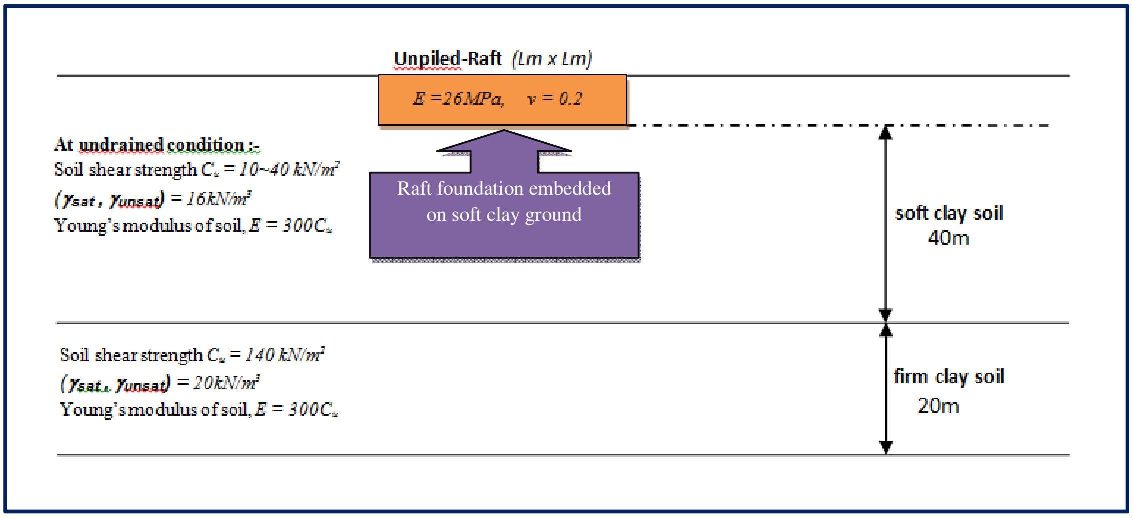

Figure 3.1.1: Cross-Section of Raft Foundation

The basic problem is illustrated in Figure. 3.1.1. This diagram shows the cross-section of a square raft foundation model constructed over a top layer of soft clay known as Kallang Formation with thickness as deep as 40m overlying another layer of firmer soil known as Old Alluvium with maximum thickness of 20m.

To develop simplified design techniques on bearing capacity of foundation against settlement for quick assessment and preliminary design use, together with design pedagogy flowcharts, step-by-step procedures and worked examples, the following range of matrix parameters identified for desktop analyses and investigation work are used:

- Square raft foundation sizes, $L = 5x5, 10x10, 20x20\ m^2$
- Square raft foundation thickness, $t = 5\%L, 10\%L, 15\%L$
- Undrained shear strength of soil at top layer, $C_u = 10, 20, 30, 40\ kPa$
- Young's Modulus of soil at top layer, $E = 300C_u\ kPa$

- Saturated density of the soil at top layer, γ_{sat}= 16kN/m^3

- Saturated density of the soil at bottom layer, γ_{sat}= 20kN/m^3

- Immediate total maximum vertical settlement, δ = *10mm, 25mm, 50mm and 100mm (however, focus will be on 25mm)*

3.2 Analysis Procedure for Raft Foundation

Lists of combined load cases used for the analyses and computation works are derived from different mixture of element's parameters (soils & concrete from the raft structure) highlighted in Para 3.1. These 36 combined load cases for the undrained soil conditions mentioned are enclosed in Appendix A.

All raft models are modelled using 3-D Plaxis Foundation geotechnical finite element analysis software to analyse and generate the bearing capacity of foundation against settlement. Results obtained from the analyses are further justified theoretically through calculations using elastic theory presented in bearing capacity against settlement graph, which is further used for detailed desktop studies.

During these whole analyses process, the raft element is considered and modelled as a linear elastic material and the soil as an elastoplastic medium.

3.3 Range of Parameters Considered for Piled-Raft Foundation

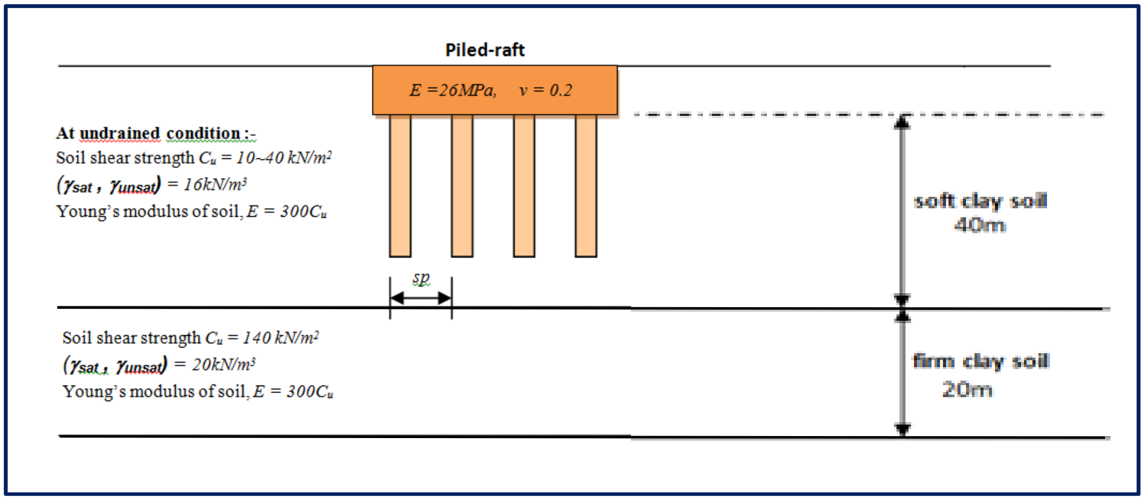

Figure 3.3.1: Cross-Section of Piled-Raft Foundation

The basic problem is illustrated in Figure 3.3.1. The diagram shows a typical cross-section of the three piled-raft foundation (5x5, 10x10, 20x20) models considered. It is embedded on a layer of soft clayey soil known as Kallang Formation with thickness as deep as 40m overlying another layer of firmer clayey soil known as Old Alluvium with maximum thickness of 20m.

The range of matrix parameters used are similar to the raft foundation (Para 3.1). Some additional parameters used include :

- Square concrete pile = *0.25m x 0.25m*
- Concrete pile length = *12m, 24, & 36m*
- Concrete pile spacing c/c, *sp = 2m & 3m square grid arrangement*
- short term maximum vertical settlement, *δ = 10mm & 25mm (focus will be on 25mm)*

3.4 Analysis Procedure for Piled-Raft Foundation

All piled-raft models are modelled using 3-D Plaxis Foundation geotechnical finite element analysis software to help analyse all the established combined load cases. All results from these analyses work are then justified theoretically and presented in some bearing capacity against settlement design charts, which are further used for detailed desktop studies.

During these analyses, the piled and raft elements are considered and modelled as a linear elastic material and the soil as an elastoplastic medium.

Small Piled-Raft Foundation (5m x 5m x 1m)

List of combined load cases derived from different mixture of parameters (soils, raft & piles) are mentioned in Para 3.3. A total of 24 combined load cases for the undrained soil conditions are developed and presented in Appendix B.

Medium Piled-Raft Foundation (10m x 10m x 2m)

List of combined load cases derived from different mixture of parameters (soils, raft & piles) are mentioned in Para 3.3 and analysed. A total of 24 combination load cases for undrained soil conditions are developed and reflected in Appendix C.

Large Piled-Raft Foundation (20m x 20m x 2m)

List of combined load cases derived from different mixture of parameters (soils, raft & piles) are mentioned in Para 3.3. A total of 96 combination load cases for undrained soil condition are developed and presented in Appendix D.

3.5 Finite Element Model for Raft and Piled-Raft Foundation

Only quarters of the square raft and piled-raft foundation are considered and used in all modelling analyses works due to two lines of symmetries. The models of the foundation are vertically loaded with uniformly distributed load to simulate its total permissible loads. Since the assessments are on bearing capacity, the analyses may be limited to basic linear models such as the Mohr-Coulomb model. In addition, based on the cohesive materials used, it is also preferable to use a simpler constitutive model; Mohr-Coulomb model which is a relatively quick and simple way to model the behaviour of soils.

In general, Mohr-Coulomb model is a well-established theory and serves as first order model. It is an elastic-perfectly plastic model that is often used to model soil behaviours e.g. deformation and failure. It is simple to use and requires five parameters, which are generally familiar to most geotechnical engineers and could be obtained from basic tests on soil samples. These parameters are listed as follows:

E : *Young's Modulus (kPa)*

v : *Poisson's ratio*

φ: *Friction angle (°)*

c : *Cohesion (kPa)*

Ψ : *Dilatancy angle (°)*

Since pore water cannot resist shear, the soil grains resist all shear stresses only. Hence, Plaxis manual has suggested adopting effective Poisson's ratio of 0.35, which is equivalent to undrained Poisson's ratio of 0.5 for all undrained condition analyses.

Boundary conditions in this study are :

- the horizontal boundary is placed three times the width of raft measured from the model symmetrical axis;

- the vertical boundary is placed until the bottom of the stiff clay. It is sixty metres under the ground surface.

Screenshots on the boundary conditions considered in both typical raft and piled-raft foundations are shown in Figure 3.5.1 Figure 3.5.2 respectively.

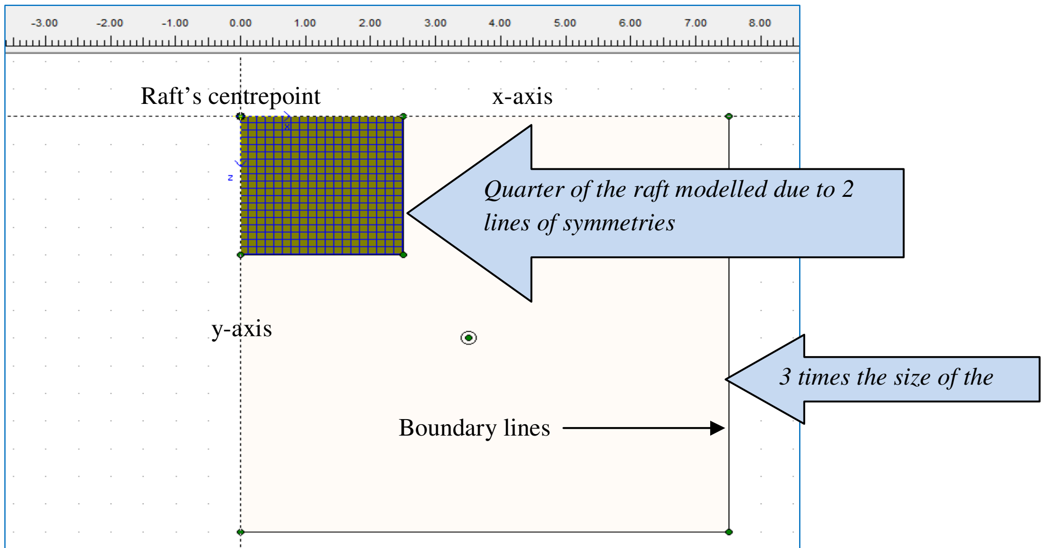

Figure 3.5.1: Plan View – Typical Qtr of Raft

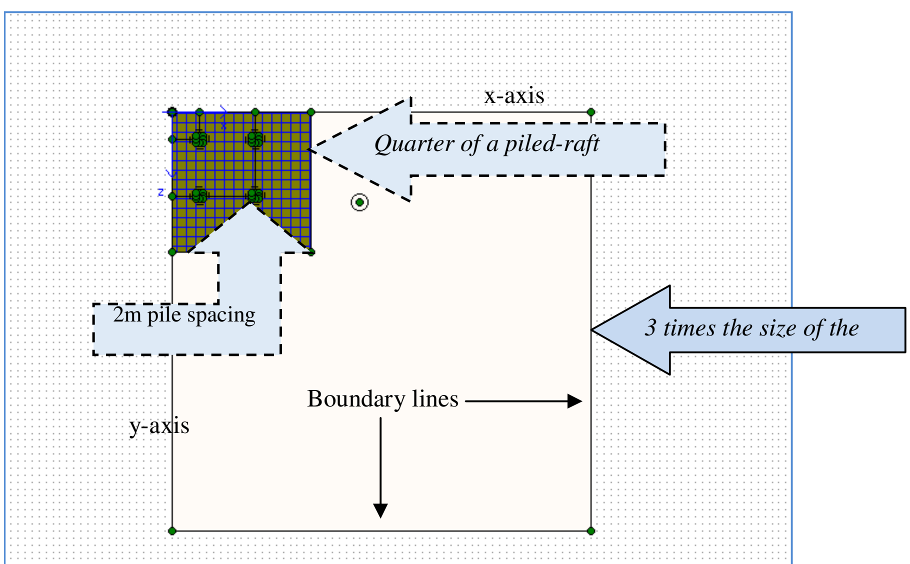

Figure 3.5.2: Plan View – Typical Qtr of Piled-Raft

3.6 Computer Assisted Analysis for Raft and Piled-Raft Foundation

To produce simplified reinforced concrete raft and piled-raft foundation design techniques, 3-D finite-element analysis that would allow very rigorous treatment of soil-structure interaction to take place are used in the numerical study.

One of the main problems in numerical simulation of raft model is the contact between the soil and the raft. Since sliding is possible to occur on the contact zone, to present the realistic condition, interface elements on the contact zone are necessary to be modelled. In the present study, to simulate the soil-structure interaction relationship, soil-structure friction strength reduction factor at interface is used in the analysis work.

Mohr-Coulomb model, which is a first order model used to assess the bearing capacity or slope stability is used in this study. Other material properties adopted in the analysis input includes:-

- Imposed vertical uniformly distributed load, W_{udl}

- Soil-structure friction strength reduction factor at interface, $R_{inter} = 0.67$

- Young's Modulus of raft, $E = 26MPa$

- Effective Poisson's ratio for top layer soil, $v_1 = 0.35$

- Effective Poisson's ratio for bottom layer soil, $v_2 = 0.3$

- Poisson's ratio for raft, $v_3 = 0.2$

Figure 3.6.1 and Figure 3.6.2 show some typical loaded quarter-size raft and piled-raft models subjected to uniformly distributed loads being analysed by the 3D-Plaxis Foundation software.

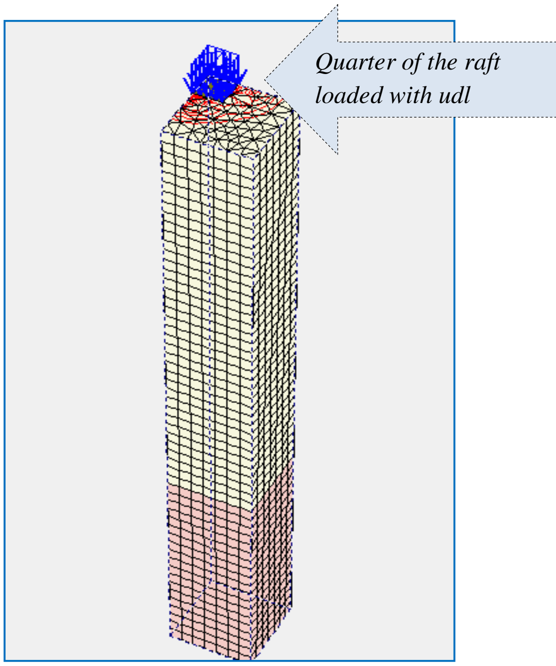

Figure 3.6.1: Loaded Raft Foundation

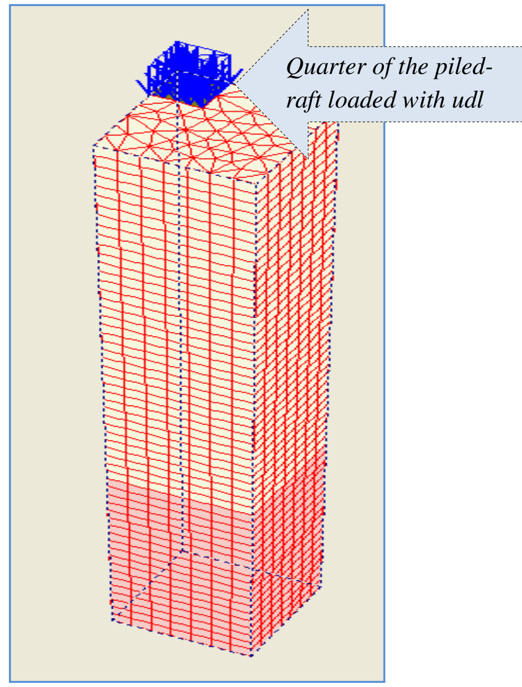

Figure 3.6.2: Loaded Piled-Raft Foundation

Figure 3.6.3 and Figure 3.6.4 show some typical deformed raft and piled-raft structure foundation models that have been subjected to an applied uniformly distributed load. Pictures are screenshot from some of the analyses work.

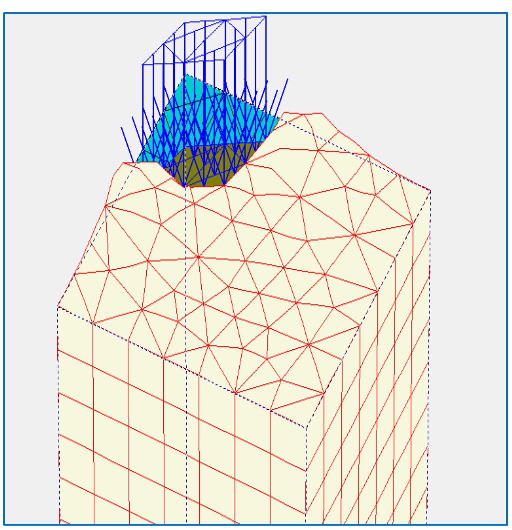

Figure 3.4.3: Deformed Raft Foundation

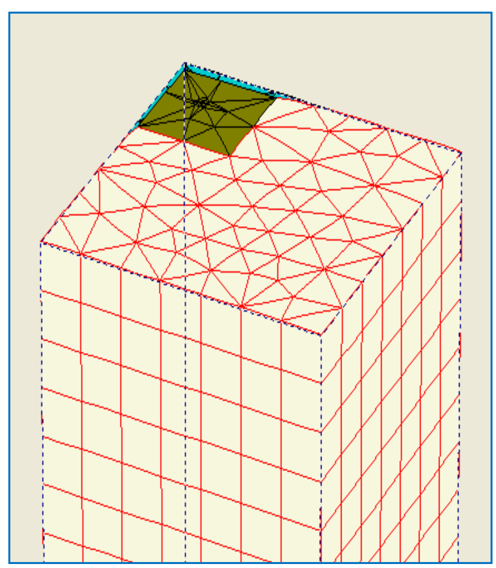

Figure 3.4.4: Deformed Piled-Raft Foundation

CHAPTER 4

FINITE ELEMENT MODELLING AND ANALYSIS

CHAPTER 4: FINITE ELEMENT MODELLING AND ANALYSIS

4.1 Raft Thicknesses for Raft Foundation

A typical square raft foundation size of 5m x 5m with combination of various thicknesses subjected to different load cases (from Appendix A) are used to model and evaluate the sensitivity of the thickness of the raft based on the principle of bearing capacity of foundation against settlement behaviours.

The analyses and computation results produced are presented in the four figures (Figures 4.1.1 to 4.1.4) below which cover studies on the sensitivity of the raft thickness ranging from 5%*L* to 15%*L* where *L* denotes the length of the raft.

The foundation are founded on the undrained shear strength of soft clayey soil at the top layer (C_u = 10kN/m^2 to 40kN/m^2) which is overlying another layer of firmer clayey soil with C_u = 140kN/m^2.

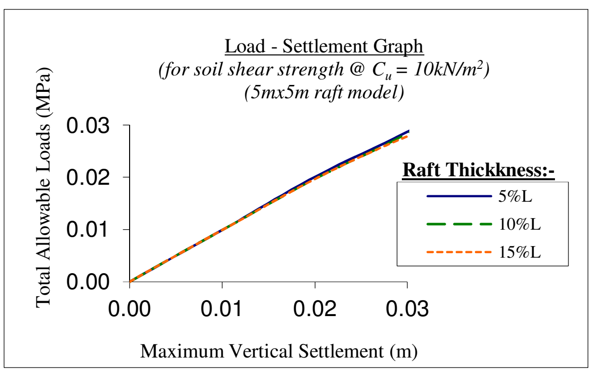

Figure 4.1.1

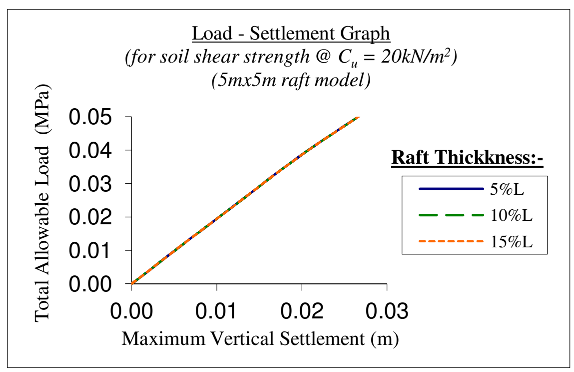

Figure 4.1.2

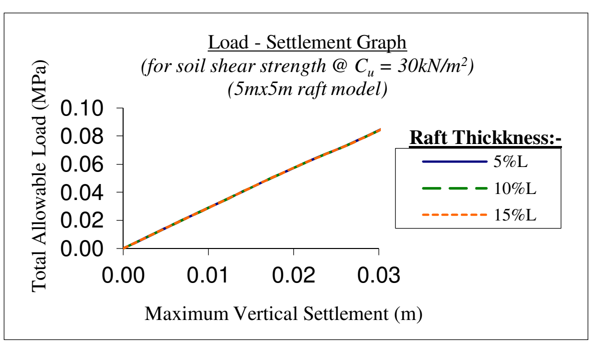

Figure 4.1.3

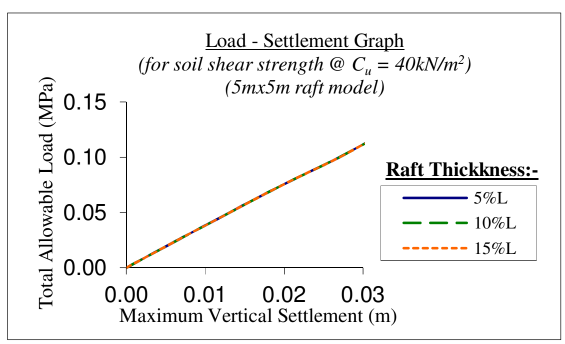

Figure 4.1.4

Figure 4.1.1 to 4.1.4 show the computation results of bearing capacity against settlement behaviours based on different thicknesses of the raft (0.25m, 0.5m and 0.75m) under different shear strength of soils (C_u=10kN/m^2 to C_u=40kN/m^2). The bearing capacity and settlement curves are almost the same for all the three different thicknesses of the raft modelled presented under different shear strength of soils. In general, as the shear strength of the soils become firmer, the rate of settlements of the raft foundation decreases.

In summary, all four figures (Figure 4.1.1 to 4.1.4) show consistent results on the bearing capacity against settlement behaviours and show that thickness of the raft has no influence on the bearing capacity against settlement behaviours. It is also noted that any increase in the shear strength of the soils would correspondingly increases the total allowable load.

In general, the bearing capacity show linear behaviours and these findings have been concurred with some literature *(Widjojo, A. and Fred, H., 2001; Poulos, 2007; Alireza et. al., 2014).*

4.2 Raft Sizes

With the study on the significance of the raft thickness completed, the next focus is on the significance of the size of the raft foundation. To begin with, the three square raft foundations with different sizes have been identified (5m x 5m, 10m x 10m & 20m x 20m) and named as small, medium and large foundation respectively. These three foundation models are set up and analysed; all rafts are subjected to uniformly distributed loads. The bearing capacity are exported and presented in Figure 4.2.1 to Figure 4.2.3 respectively to the three sizes mentioned.

In general, the small raft tends to achieve highest bearing capacity against settlement behaviour and this finding has concurred with *De Beer (1965)* finding on the bearing capacity decreasing with an increase in foundation sizes.

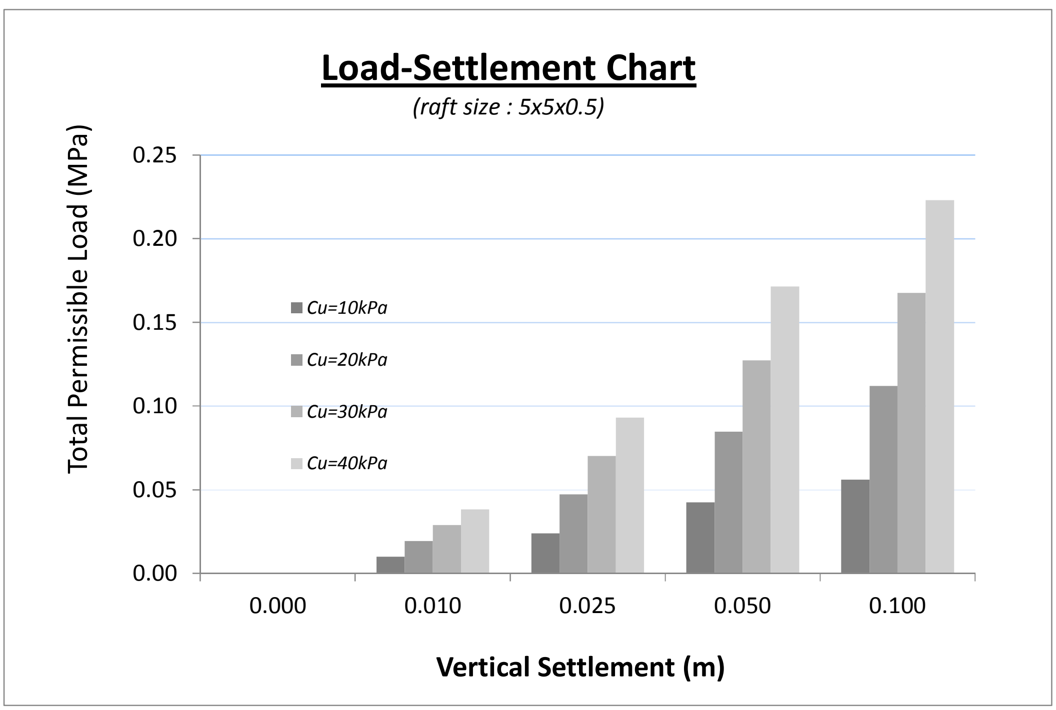

Figure 4.2.1

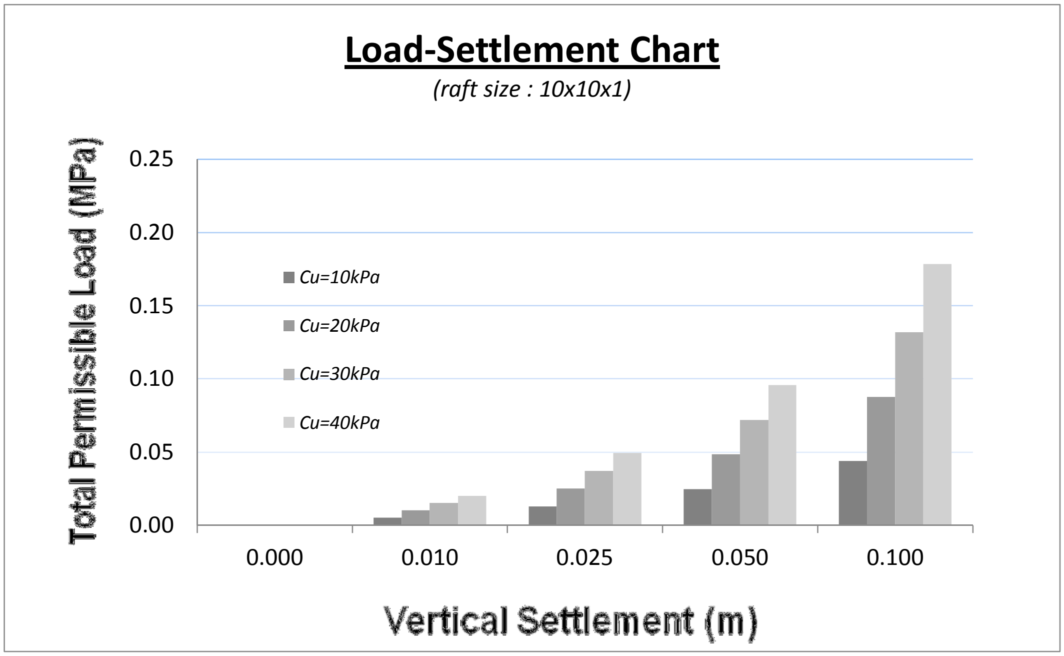

Figure 4.2.2

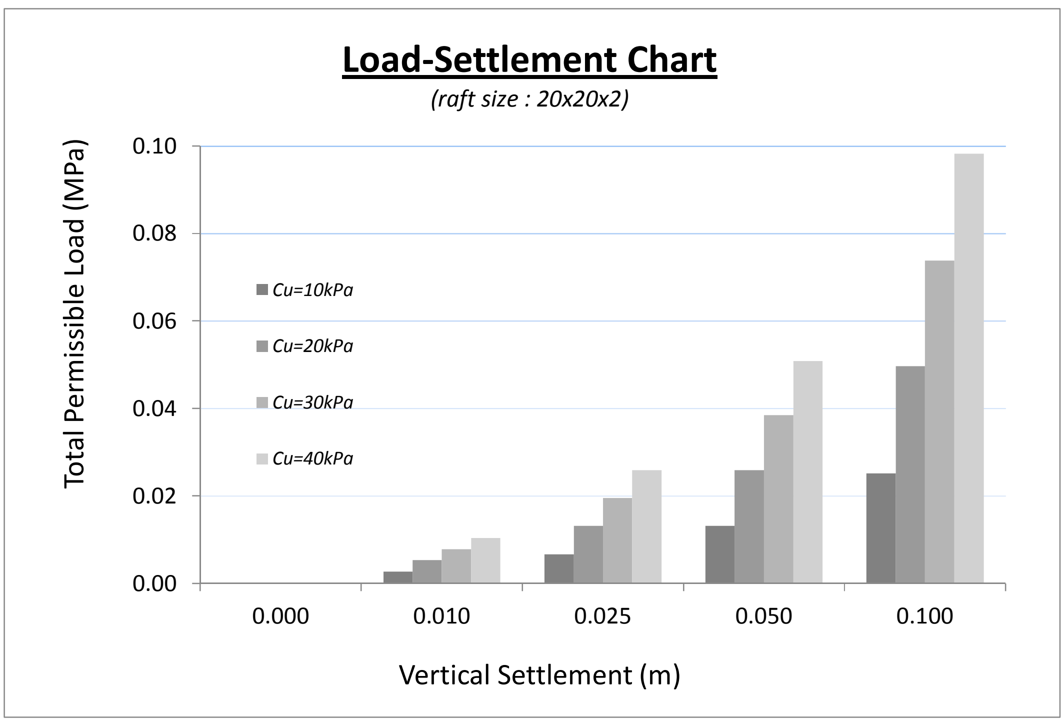

Figure 4.2.3

From these three figures (Fig. 4.2.1 to Fig4.2.3), the computation data are further studies, consolidated and integrated to transform into an integrated design chart shown in Figure 4.2.4. The intention for this design chart presentation is to reflect the significance of the raft with different sizes based on their load bearing against settlement behaviours aspect.

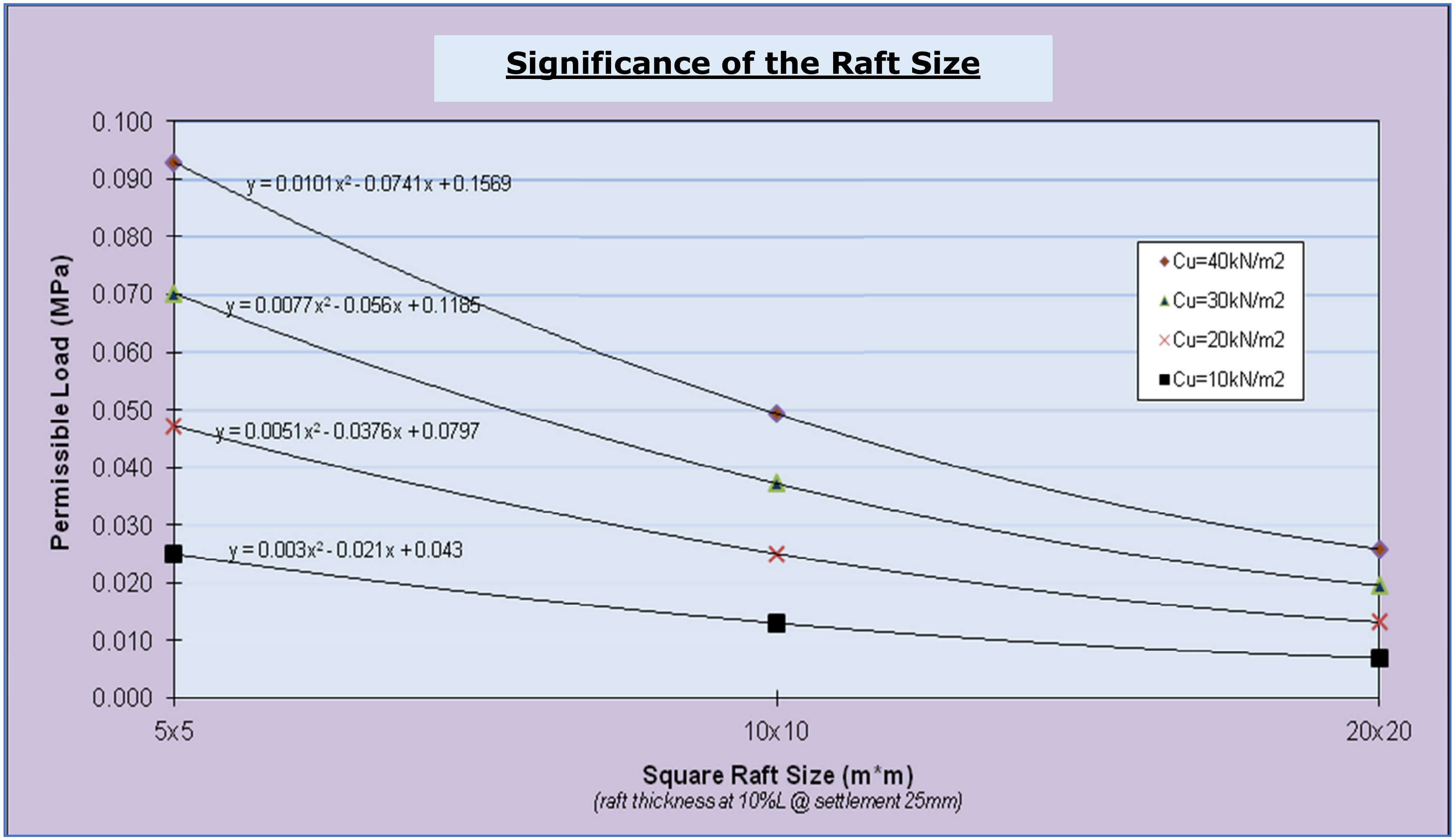

Figure 4.2.4: Significance of the Raft Size

4.3 Critical Settlement Point for Raft Foundation

Earlier work done on the sensitivity studies on the thickness and size of raft foundation based on their bearing capacity against settlement behaviours have concluded that thickness of the raft has little influence on it while the bearing capacity of foundation has decreased with its foundation size increased (See Para 4.1 and Para 4.2 respectively).

At this stage, the model of the small raft is selected for further study on it critical settlement behaviour from the soil-structure interaction relationships. The setting up of this model is shown in Figure 4.3.1.

Study done on this small raft foundation model would be used to create the upper threshold level on the design chart since it is expected to produce the highest bearing capacity as shown in Figure 4.2.4. Hence, the largest raft size (20m x 20m) foundation model would then be used to create the lower threshold level on the design chart since it is expected to produce the lowest bearing capacity as shown in Figure 4.2.4.

To begin with, three critical total vertical settlement points on the small raft model are identified for the bearing capacity against settlement behaviour study is shown in Figure 4.3.1.

These three identified critical points are namely :-

i) Centre-Point;

ii) Middle-of-Edge;

iii) Corner-of-Raft.

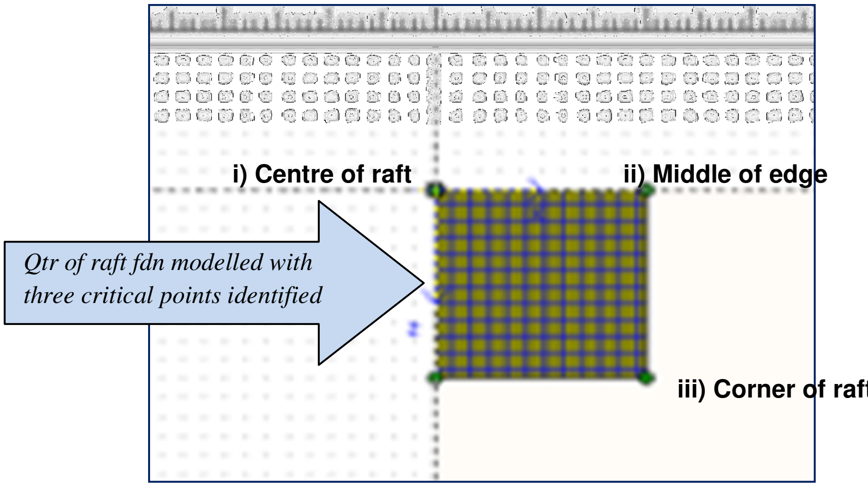

Figure 4.3.1: Plan View – Qtr of Raft Foundation

This small raft foundation is modelled with uniformly distributed load together with the self-weight of the structure. The analysed results are retrieved are exported for desktop studies and outcomes are presented in Figure 4.3.2 & Figure 4.3.3.

In Figure 4.3.2, the presented bearing capacity of foundation against settlement behaviours generated from the computation work revealed from the most to the least critical settlement points occurred at the centre of the raft, followed by the middle of edge and finally corner of the raft respectively.

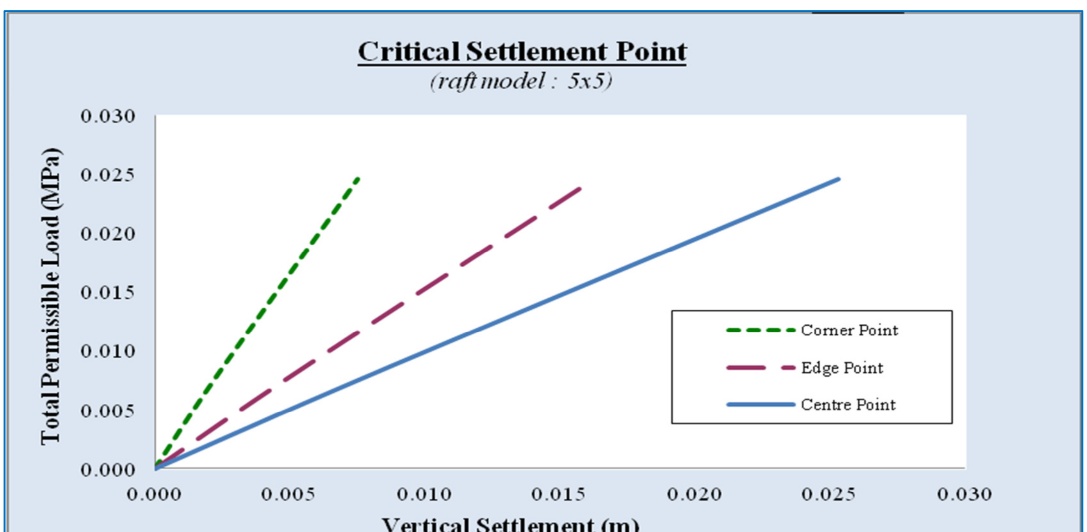

Figure 4.3.2: Critical Settlement Point

To further explores the "critical direction" on the bearing capacity of foundation against differential settlements, two bearing capacities of foundation against settlement directions are identified for the studies. These two critical directions are namely from points (see Fig. 4.3.1) :-

i) centre of the raft to the middle of edge of the raft;

ii) centre of the raft to the corner of the raft.

In Figure 4.3.3, the presented bearing capacity of soils against differential settlement has behaved most critical on the "direction" from the centre of the raft to the corner of the raft.

These findings (Fig. 4.3.2 & Fig. 4.3.3) have concurred with other researchers' report concluding that the most critical settlement points are from centre of the raft to the corner of the raft *(Widjojo, A. and Fred, H., 2001).*

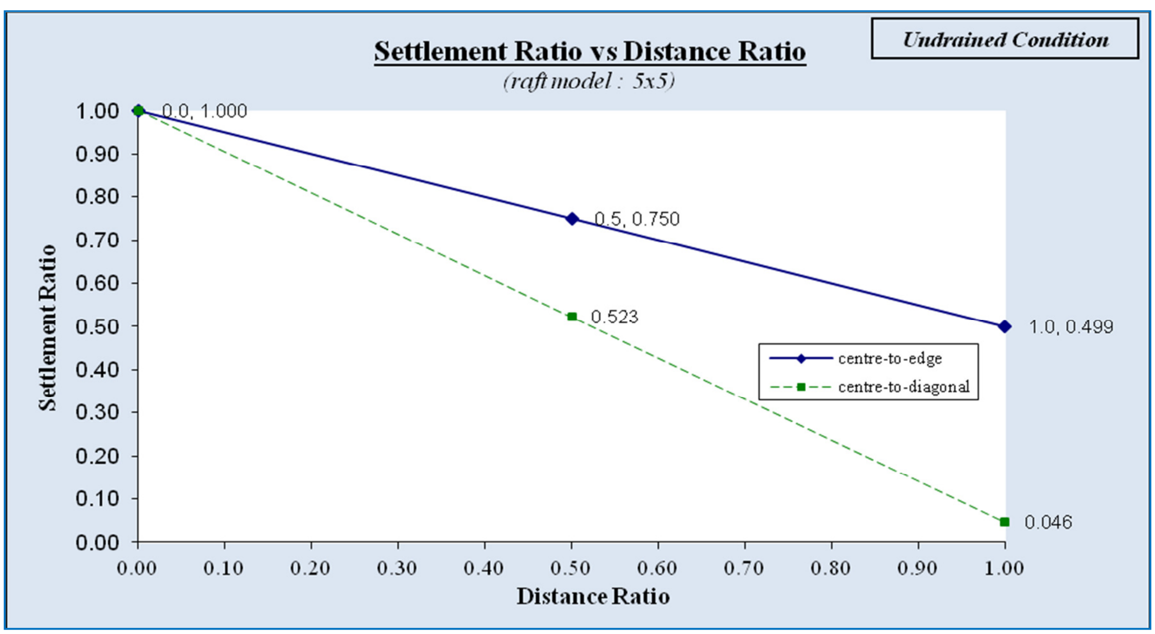

Figure 4.3.3: Settlement Ratio vs Distance Ratio

With this evidence established, it helped to set the path for reading of differential settlement to be taken from this direction:- centre to corner of the raft. The main reason for this is obvious since it governs the worst-case scenario on the bearing capacity of foundation against differential settlement studies.

4.4 Behaviour of Raft Foundation

This section presents the behaviours of some typical raft foundations modelled in this study.

Graph shows in Figure 4.4.1 having the bearing capacity of foundation against the length-ratio of the raft foundation at 25mm settlement behaviours. The displacement pattern reflected a typical placement profile of the raft in bowl-shaped or saddle-shaped pressure distribution curves behaviour.

Considering the displacement from corner-centre-corner of the raft structure section, this displacement pattern shall represent a nominal average type of displacement experienced along the raft.

From this analytical result, it could be suggested that the raft model has acted and behaved like a flexible structure foundation and having non-uniformly total vertical settlement pattern.

In addition, the difference in the differential settlement from centre-to-edge of the raft is about 60% which has concurred with *Terzaghi & Peck's (1948)* suggestion that the differential settlement is unlikely to exceed 75% of the maximum settlement (refer to Para 1.4).

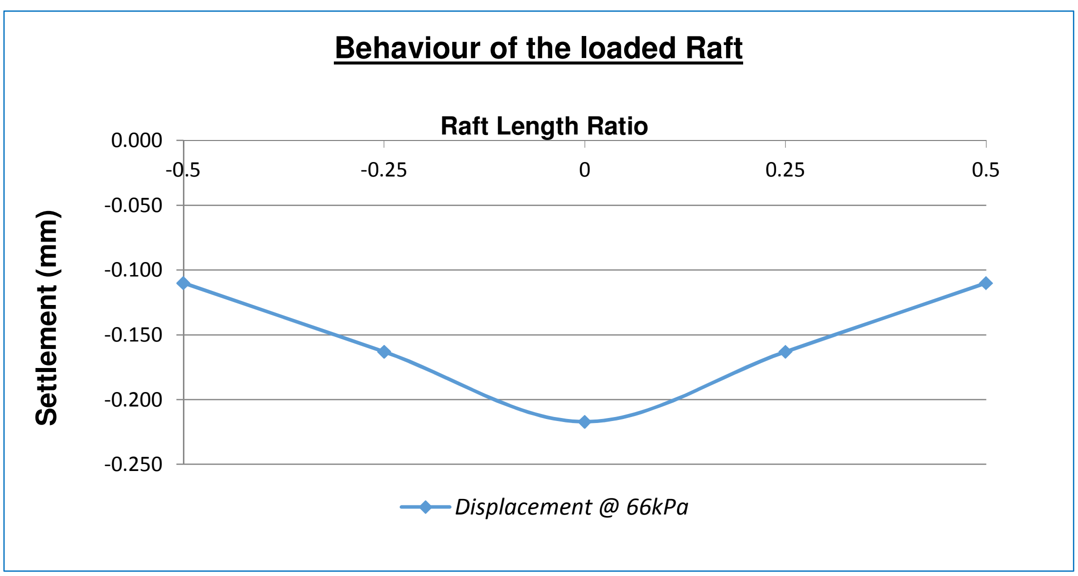

Figure 4.4.1: Behaviour of the Loaded Raft

4.5 Bearing Capacity of Raft Foundation

To conduct study on the efficiency of the bearing capacity of raft foundation on it size, small, medium and large (5x5, 10mx10m & 20m x 20m) are once again use for the study.

Vertical loads are applied uniformly on the raft. The computation results are exported and presented in the following three figures (Fig. 4.5.1 to Fig. 4.5.3).

From these three figures (Fig. 4.5.1 to Fig. 4.5.3), it is noticeable that the small raft foundation model managed to achieve the highest bearing capacity and the largest raft foundation model has resulted with the lowest bearing capacity of foundation against settlement behaviours.

In general, these three figures (Fig. 4.5.1 to Fig. 4.5.3) present also illustrated and reflected the rate of settlements for the bearing capacity appeared to increase linearly with the increment of the undrained shear strength of soils and bearing loads in the elastic limits range.

These three figures (Fig. 4.5.1 to Fig. 4.5.3) are then further consolidated to develop into an integrated design chart shown in Figure 5.1.1 to permit quick assessment during preliminary design stage for reference on the bearing capacity of foundation against settlement.

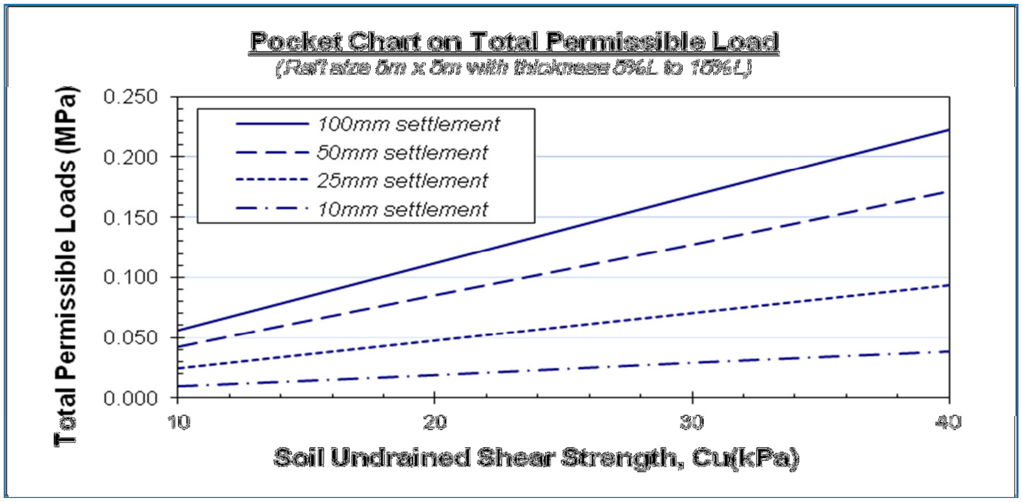

Figure 4.5.1: Bearing Capacity for Small Raft

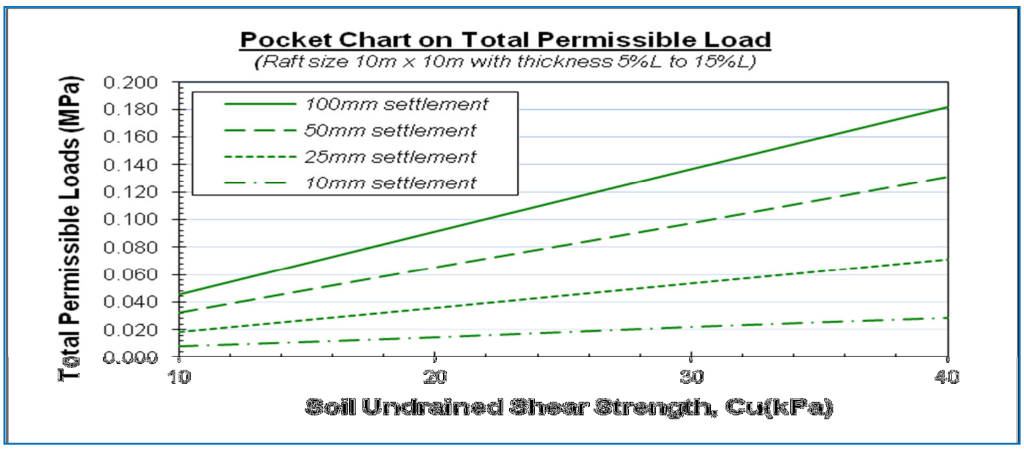

Figure 4.5.2: Bearing Capacity for Medium Raft

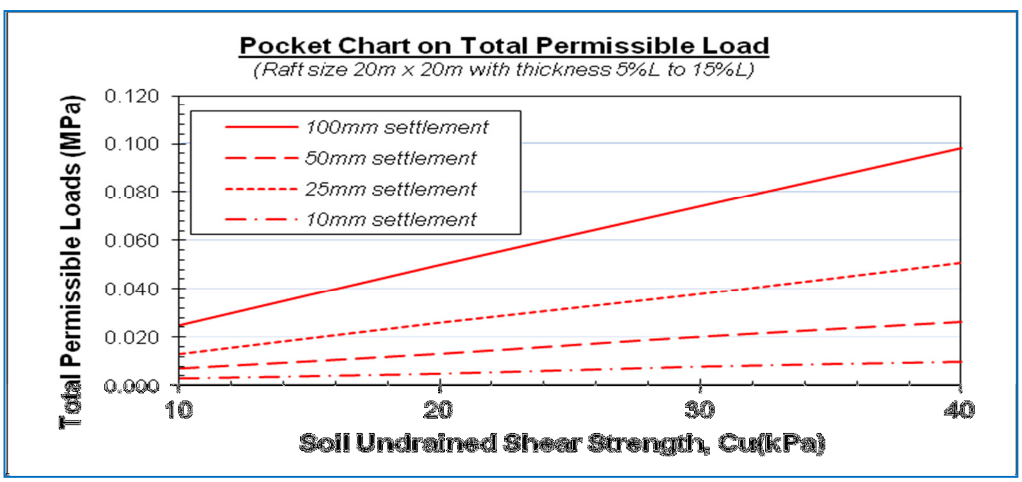

Figure 4.5.3: Bearing Capacity for Large Raft

4.6 Raft Thicknesses for Piled-Raft Foundation

Refer to Para 4.1, investigation works done on raft foundations have revealed thickness of the raft having little influence on the bearing capacity of foundation against settlement curve, with the assumption that the raft is fully embedded in a thick layer of soft clayey soil (Kallang Formation) overlying another layer of firmer clayey soil (Old Alluvium) under undrained conditions. *Poulos (2001)* has also highlighted that neither the maximum settlement nor the percentage of load carried by the piles is sensitive to the thickness of the raft. However, as expected, increasing the raft thickness would help to reduce the differential settlement, but would generally increase the maximum bending moment of the structure *(Alireza et. al., 2014).*

In this study, the piled-raft's slab thickness of 20% the length would be considered and used for the desktop studies.

4.7 Raft Size on Piled-Raft Foundation

Refer to Para 4.2, the investigated results have concluded small raft foundation been the most effective foundation in bearing capacity against settlement behaviours compared to larger raft foundation.

<u>Small Piled-Raft Foundation (5m x 5m)</u>

4.8 Small Piled-Raft Critical Settlement Point

With studies on thickness and size of the raft foundation done, following would be on the selection of small piled-raft model to establish it bearing capacity against settlement behaviours to be the highest threshold level on the developed design chart. Hence, this typical model of 5m x 5m piled-raft foundation is chosen (Fig. 4.8.1) for detailed desktop studies for it critical settlement point.

To begin with, the three critical settlement points are identified for the studies and the analyses outputs are shown in Figure 4.8.1.

The three identified critical points are namely at :-

i) Centre-Point;

ii) Middle-of-Edge;

iii) Corner-of-Raft.

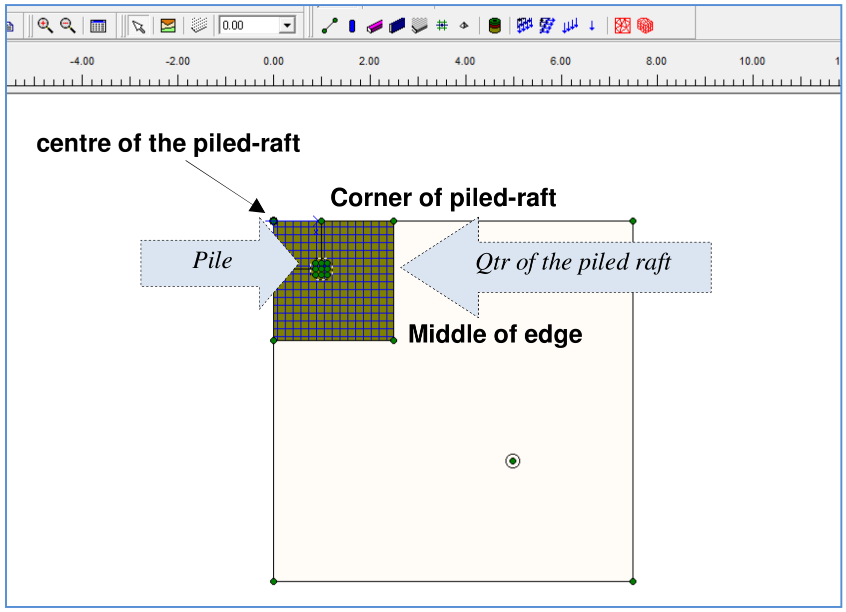

Figure 4.8.1: Plan View – Qtr of Small Piled-Raft Foundation

To present the behaviour of small piled-raft, an applied uniformly distributed load is spreaded over the top of the small piled-raft foundation. A typical set of analysed results are retrieved, digressed and summarised in Figure 4.8.2 and Figure 4.8.3.

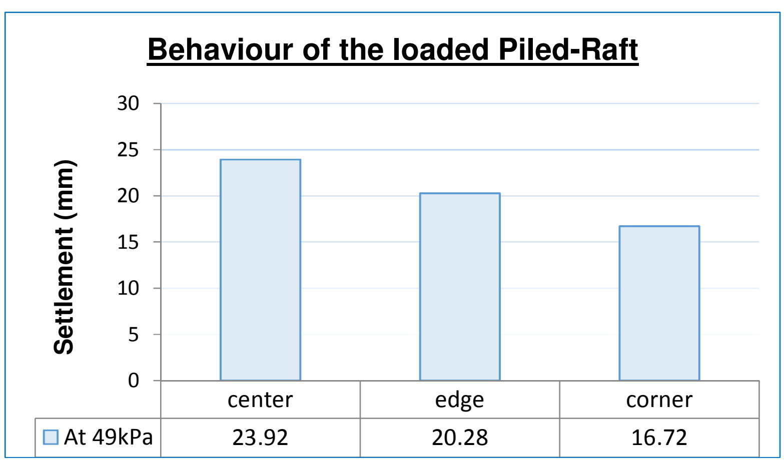

Figure 4.8.2: Behaviour of Small Piled-Raft Model (with 2m pile spacing)

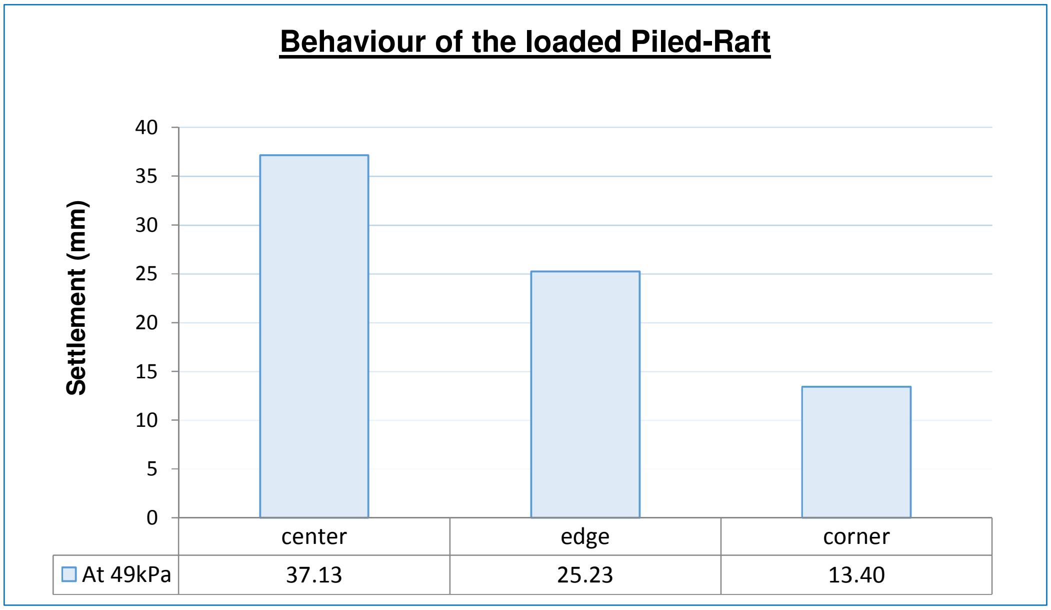

Figure 4.8.3: Behaviour of Small Piled-Raft Model (with 3m pile spacing)

Figures 4.8.2 & 4.8.3 show consistent patterns on the bearing capacity against settlement behaviours of foundation under different pile spacing *(2m and 3m)* arrangements.

To conclude, the most critical settlement point has fallen on the centre-point of the piled-raft for both the 2m and 3m piles spacing arrangement. From Figure 4.8.2 and Figure 4.8.3, both bearing capacity of foundation against settlement design charts (2m & 3m piles spacing at square grid arrangement) pictured a saddle-shaped load pressure distribution patterns similar to Figure 4.4.1.

Consequently, these suggested the piled-raft foundation has acted and behaved as a flexible structure. This has concurred with the findings from *Poulos (2001)* that the differential settlement between the centre and corner piles does not change in a regular fashion with the number of piles.

4.9 Influence Factors on Small Pile-Raft Performance

The two figures (Fig. 4.9.1 & Fig. 4.9.2) are the outputs generated from the analysed models. These two graphs made known the bearing capacity of the piled-raft foundations increased linearly with stiffer soil conditions from 10kPa to 40kPa.

Comparison on both figures (Fig. 4.9.1 & 4.9.2) also revealed that a foundation with closer piles spacing arrangement are technically a more viable option as it would help to increase the allowable load carrying capacity of the piled-raft foundation. This could be explained from these two figures again; a piled-raft foundation with 12m pile-length at 2m spacing is seen to be performing as much better as ones with 36m pile-length at 3m spacing, in term of bearing capacity. The finding also concurred with *Gopinath et. al. (2010)* that the average settlement is found to be increased when the pile spacing is more.

In addition, it is also noted the factor of influence on the length of the piles tend to turn insignificant when the spacing of the piles increased from 2m to 3m.

Generally, spacing of piles plays an important role on the performance of piled-raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft and the load shared by the piles. The reduction on pile spacing has the effect of reducing the piled-raft settlement while the maximum bending moment and the load sharing are not affected much by increasing of the pile lengths. The axial load is observed to be the maximum at the top of the pile, and it reduces with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases. These findings have concurred with *Baleshwas et. al. (2011).*

Hence, these suggested that when designing for piled-raft foundation structure, it would be more prudent to consider having a closer pile spacing arrangement as a priority over having provision of longer pile length in soft soil condition, whenever possible.

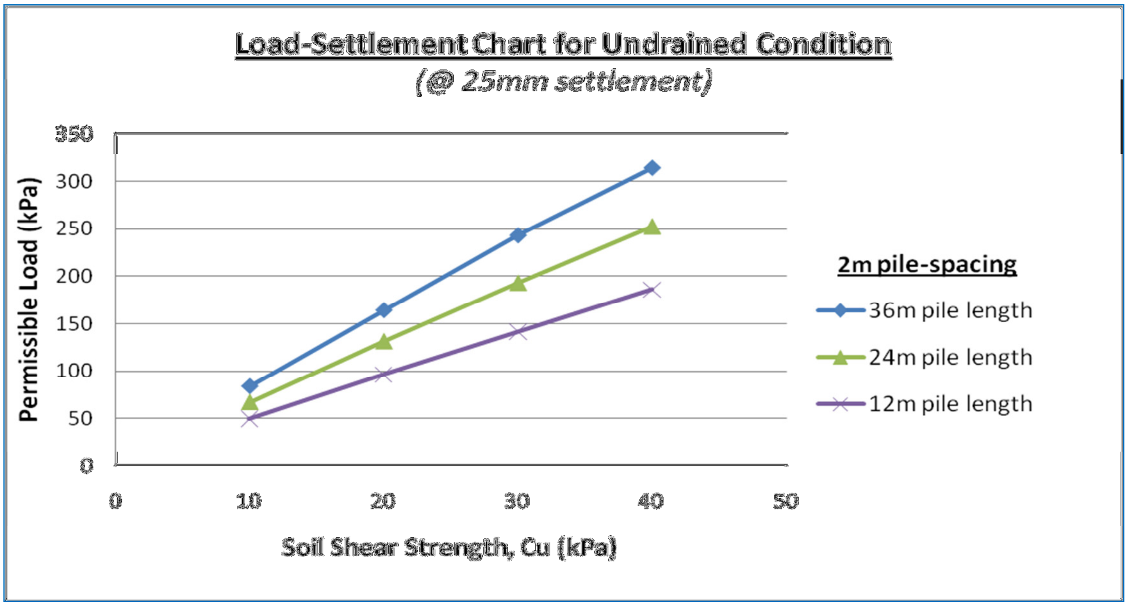

Figure 4.9.1: Permissible Bearing Load versus Undrained Shear Strength of Clay

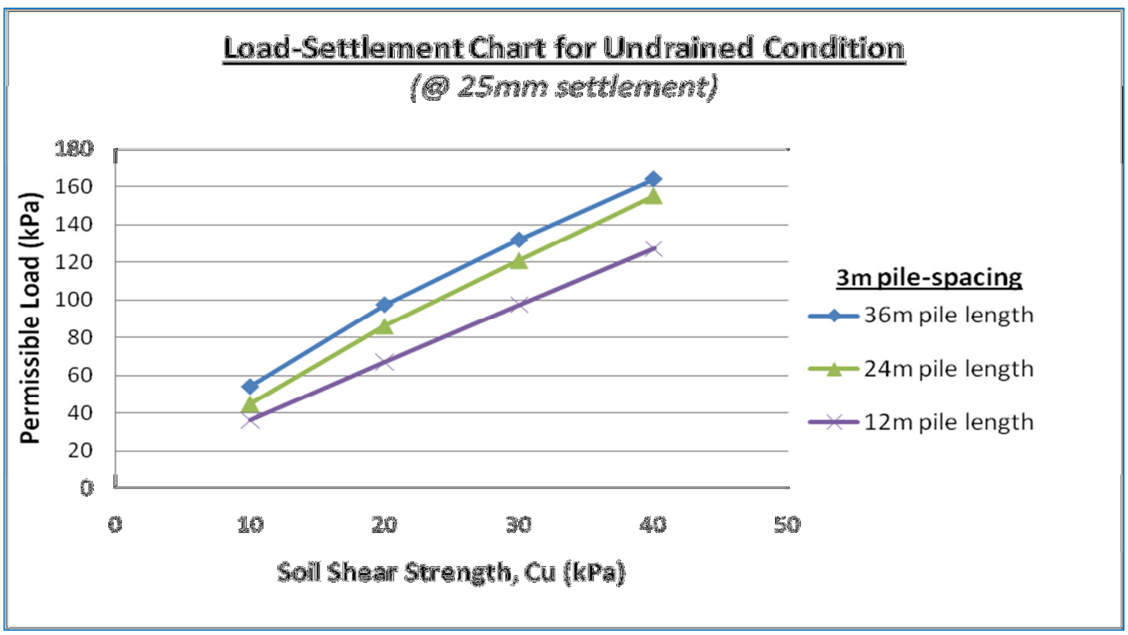

Figure 4.9.2: Permissible Bearing Load versus Undrained Shear Strength of Clay

4.10 Bearing Capacity of Small Piled-Raft Foundation

Figure 4.9.1 and Figure 4.9.2 revealed the significant of the pile spacing and pile length on the bearing capacity of foundation against settlement behaviours. It is also notable that the patterns of bearing capacity are also very sensitive to any changes in the shear strength of soils. In addition, the conditions of the ground could cause changes to the rate of settlements on the piled-raft foundations and its behaviours too.

In general, the rate of settlements for the bearing capacity seems to increase linearly with the increment of the shear strength of soils.

Further study into the details also illustrated that usually the pile base resistance is also often not fully mobilised during the short-term period. Even if the base resistance is mobilised, the distinction between the shaft and base resistance might not be exact. This has concurred with *Widjojo, A. and Fred, H. (2001),* who reported for deep piles that the tip resistance generally is smaller than the side resistance.

Medium Piled-Raft Foundation (10m x 10m)

4.11 Medium Piled-Raft Critical Settlement Point

With studies on thickness and size of raft foundation done, following would be on the selection of the piled-raft model to be the medium size piled-raft foundation on the developing design chart.

Hence, the typical model of 10m x 10m piled-raft foundation is picked (Fig. 4.11.1) for detailed desktop studies on this studies.

To begin with, three critical settlement points are identified for the studies and the computation outputs are shown in Figure 4.11.1.

The three identified critical points are namely at :-

i) Centre-Point;

ii) Middle-of-Edge;

iii) Corner-of-Raft.

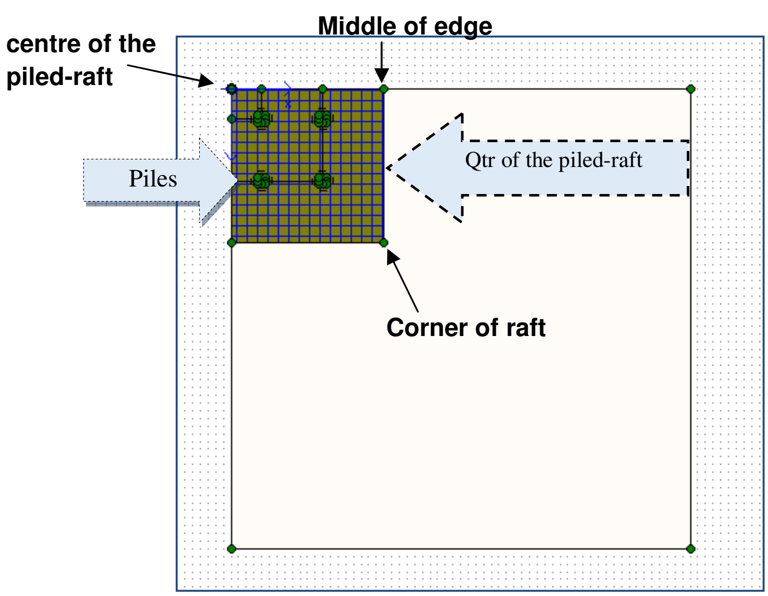

Figure 4.11.1: Plan View – Qtr of Medium Size Piled-Raft Foundation

To present the behaviour of medium piled-raft, an applied uniformly distributed load is spreaded over the top of the medium size piled-raft foundation model. Two models are created having the same total number of piles, pile length and square-grid arrangement but with different pile spacing - 2m and 3m. A typical set of analyses results are retrieved, digressed, summarised and presented in Figure 4.11.2 & Figure 4.11.3 respectively.

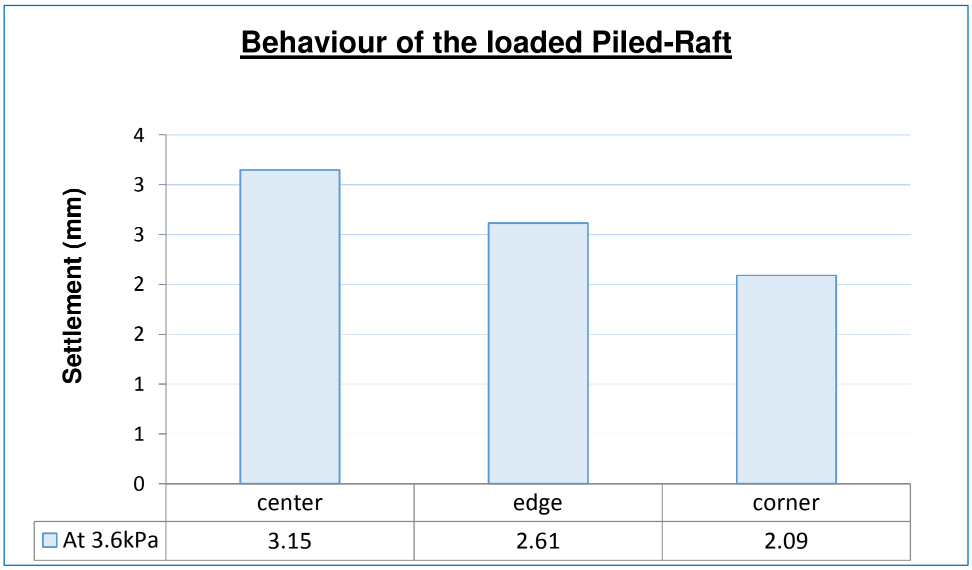

Figure 4.11.2: Behaviour of Medium Size Piled-Raft Model (2m pile spacing)

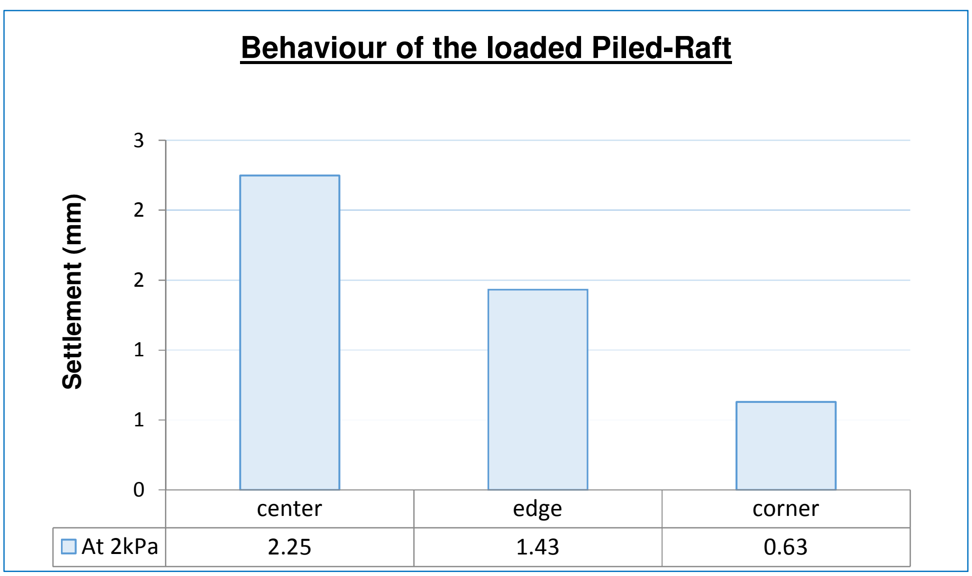

Figure 4.11.3: Behaviour of Medium Size Piled-Raft Model (3m pile spacing)

Figures 4.11.2 & 4.11.3 show consistent patterns on the bearing capacity against settlement behaviours of foundation under different pile spacing *(2m and 3m)* arrangements.

To conclude, the most critical settlement point has fallen on the centre-point of the piled-raft, for both the 2m and 3m piles spacing arrangement, followed by middle of edge and corner of the raft respectively. From Figure 4.11.2 and Figure 4.11.3, both bearing capacity of foundation against settlement design charts (2m & 3m piles spacing) pictured a saddle-shaped load pressure distribution patterns similar to Figure 4.4.1.

Consequently, this suggests the piled-raft foundation has acted and behave as a flexible foundation. This has concurred with the finding from *Poulos (2001)* that the differential settlement between the centre and corner piles does not change in a regular fashion with the number of piles.

4.12 Influence Factors on Medium Pile-Raft Performance

The two figures (Fig. 4.12.1 & Fig. 4.12.2) are the outputs generated from analysed models. These two graphs revealed the bearing capacity of the piled-raft foundation increased linearly with stiffer soil conditions from 10kPa to 40kPa.

Comparing on both figures (Fig. 4.12.1 & Fig. 4.12.2) also revealed that a foundation with closer piles spacing arrangement are technically a more viable option as it would help to increase the allowable load carrying capacity of the piled-raft foundation. This could be explained from the two figures again; the model having closer piles spacing at 2m interval produced higher load bearing-settlement capacity compared to the model with piles spaced at 3m square grid interval formation. The finding also concurred with

Gopinath et. al. (2010) that the average settlement is found to be increased when the pile spacing is more.

Generally, piles spacing plays an important role on the performance of piled-raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft and the loads to be shared by the piles. The reduction on pile spacing has the effect of reducing the piled-raft settlement while the maximum bending moment and the load sharing are not affected much by increasing of the pile lengths. The axial load is observed to be the maximum at the top of the pile, and it reduced with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases. These findings concurred with *Baleshwas et. al. (2011).*

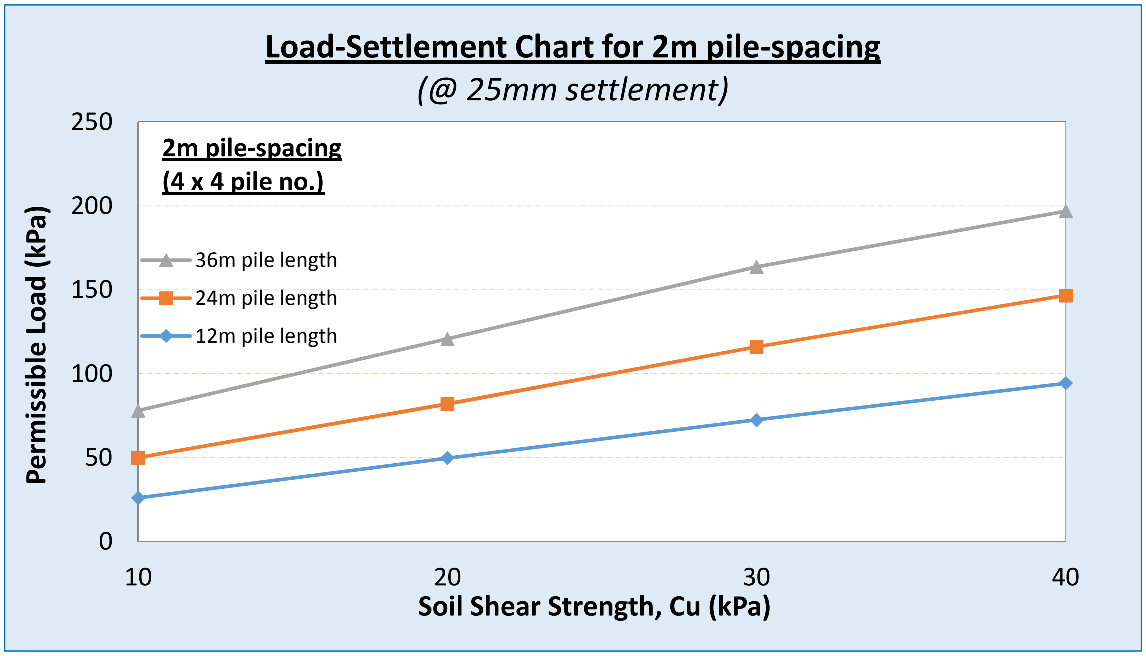

Figure 4.12.1: Permissible Bearing Load versus Undrained Shear Strength of Clay (2m pile spacing)

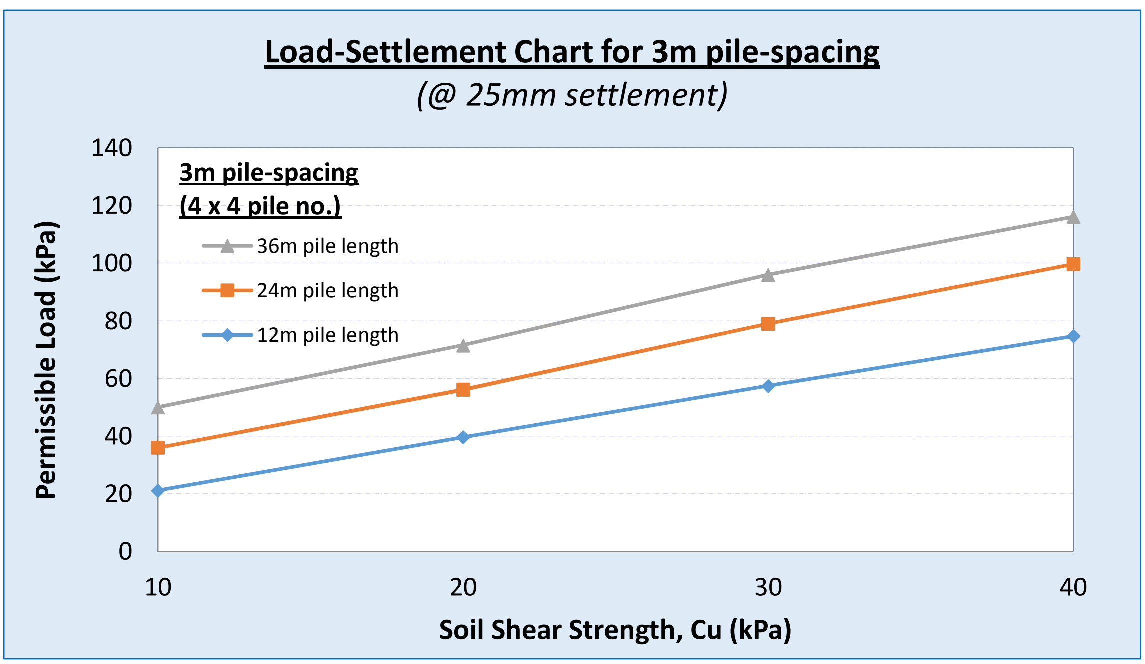

Figure 4.12.2: Permissible Bearing Load versus Undrained Shear Strength of Clay (3m pile spacing)

4.13 Bearing Capacity of Medium Piled-Raft Foundation

Figure 4.12.1 & Figure 4.12.2 revealed the significant of the pile spacing and pile length on the bearing capacity of foundation against settlement behaviours. It is also notable that the patterns of bearing capacity against settlement behaviours are also very sensitive to any changes in the shear strength of soils. In addition, the conditions of the ground could cause changes to the rate of settlements on the piled-raft foundations and its behaviours too.

In general, the rate of settlements for the load bearing against settlement seems to increase linearly with the incremental of the shear strength of soils.

Further study into the details also illustrated that usually the pile base resistance is also often not fully mobilised during the short-term period. Even if the base resistance is mobilised, the distinction between the shaft and base resistance might not be exact. This has concurred with *Widjojo, A. and Fred, H. (2001)* reported for deep piles that the tip resistance generally is smaller as compared with the side resistance.

Large Piled-Raft Foundation (20m x 20m)

4.14 Large Piled-Raft Critical Settlement Point

With studies on thickness and size of the raft foundation done, following would be on the selection of large piled-raft model to set as the lowest threshold level on the developed design chart.

Hence, the typical model of 20m x 20m piled-raft foundation is chosen (Fig. 4.14.1) for detailed desktop studies on it critical settlement points.

To begin with, the three critical settlement points are identified for the studies and the analyses outputs are shown in Figure 4.14.1.

The three identified critical points are namely at :-

i) Centre-point;

ii) Middle-of-edge;

iii) Corner-of-Raft.

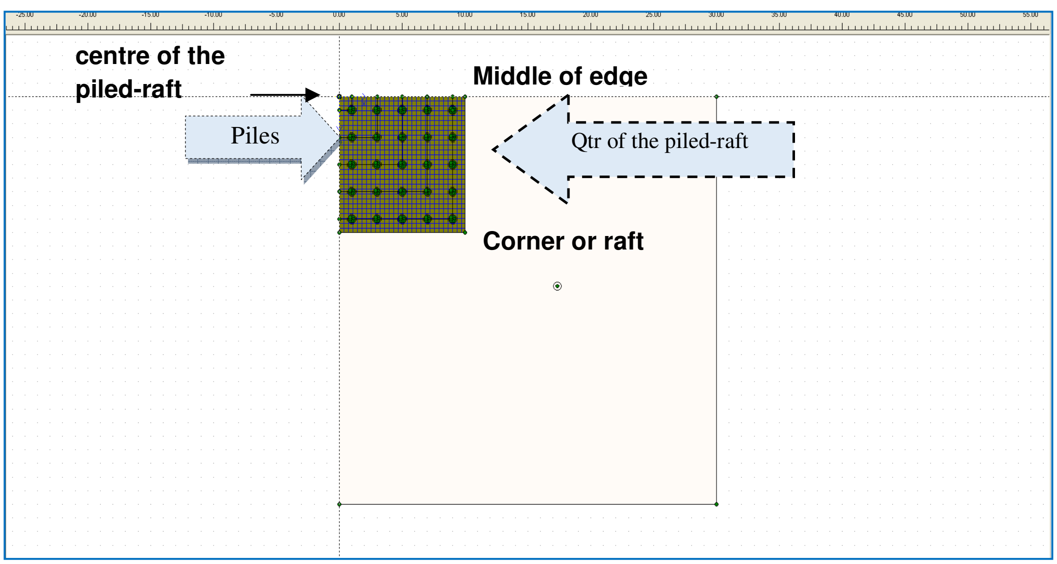

Figure 4.14.1: Plan View – Qtr of Large Piled-Raft Foundation

To present the behaviour of large piled-raft, an applied uniformly distributed load is spreaded over the top of the large piled-raft foundation. A typical set of analysed results are retrieved, digressed, summarised and presented in Figure 4.14.2 & Figure 4.14.3.

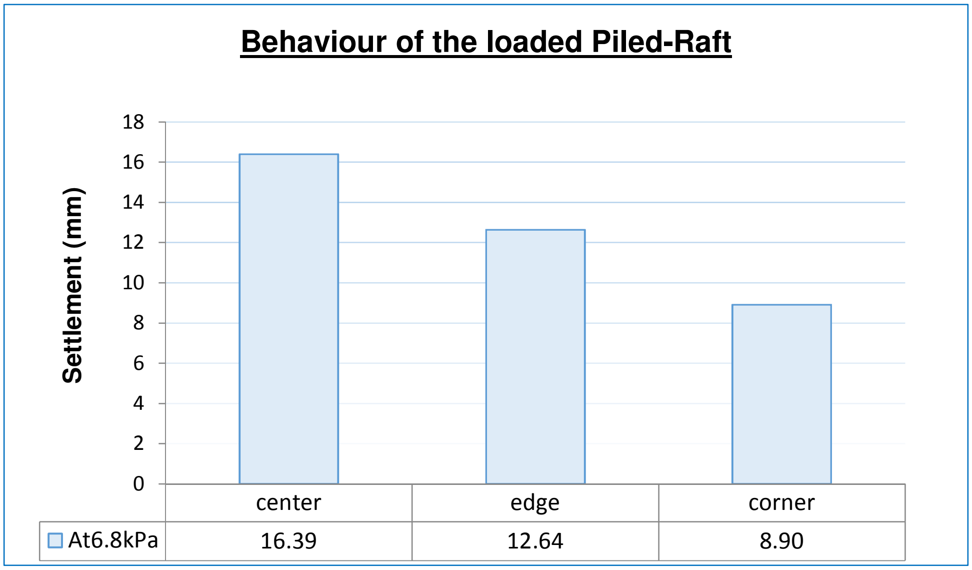

Figure 4.14.2: Behaviour of Large Piled-Raft Model (with 2m pile spacing)

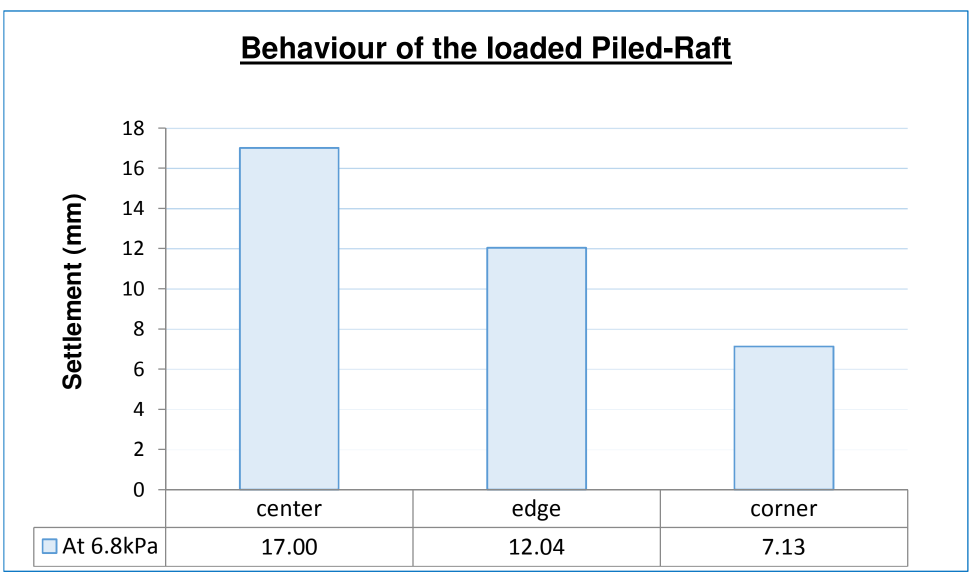

Figure 4.14.3: Behaviour of Large Piled-Raft Model (with 3m pile spacing)

Figure 4.14.2 & Figure 4.14.3 show consistent patterns on the bearing capacity against settlement behaviours of foundation under different pile spacing *(2m and 3m)* arrangements.

To conclude, the most critical settlement point has fallen on the centre-point of the piled-raft for both the 2m and 3m piles-spacing arrangement, followed by middle of edge and corner of the raft respectively. From Figure 4.14.2 & Figure 4.14.3, both bearing capacity design charts (2m & 3m piles spacing) form a saddle-shaped load pressure distribution patterns similar to Figure 4.4.1.

Consequently, these suggested the piled-raft foundation has acted and behaved as a flexible foundation. This has concurred with the finding from *Poulos (2001)* that the differential settlement between the centre and corner piles does not change in a regular fashion with the number of piles.

4.15 Influence Factors on Large Pile-Raft Performance

The eight figures (Fig. 4.15.1 to Fig. 4.15.8) are the outputs generated from the analysed models. These graphs revealed the bearing capacity of the piled-raft foundation increased linearly with stiffer soil conditions from 10kPa to 40kPa.

Comparing Figure 4.15.2 and Figure 4.15.7, both models are having same numbers of pile but different spacing (2m square-grid and 3m square-grid respectively). It has revealed that a closer piles spacing arrangement is technically a more viable option as it would help to increase the load bearing capacity. The model having closer spacing of piles at 2m interval has achieved higher bearing capacity of foundation against settlement compared to one with piles spaced at 3m square grid formation. The finding also concurred with *Gopinath et. al. (2010)* that the average settlement is found to be increase when the pile spacing is more.

Increase in numbers of pile would cause increment in the bearing capacity of foundation against settlement. Comparing Figure 4.5.1 with Figure. 4.15.5, it could be noted that the former arrangement having 2x2 number of piles has lower bearing capacity compared to 10x10 number of pile arrangement.

Generally, spacing of piles plays an important role on the performance of piled-raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft and the loads sharing by the piles. The reduction on pile spacing has the effect of reducing the piled-raft settlement while the maximum bending moment and the load sharing are not affected much by increasing of the pile lengths. The axial load is observed to be the maximum at the top of the pile, and it reduces with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases. These findings concur with *Baleshwas et. al. (2011).*

Hence, it is suggested that when designing for piled-raft foundation, it would be more prudent to consider having a closer pile spacing arrangement as a priority over having provision of longer pile length in soft soil conditions, whenever possible.

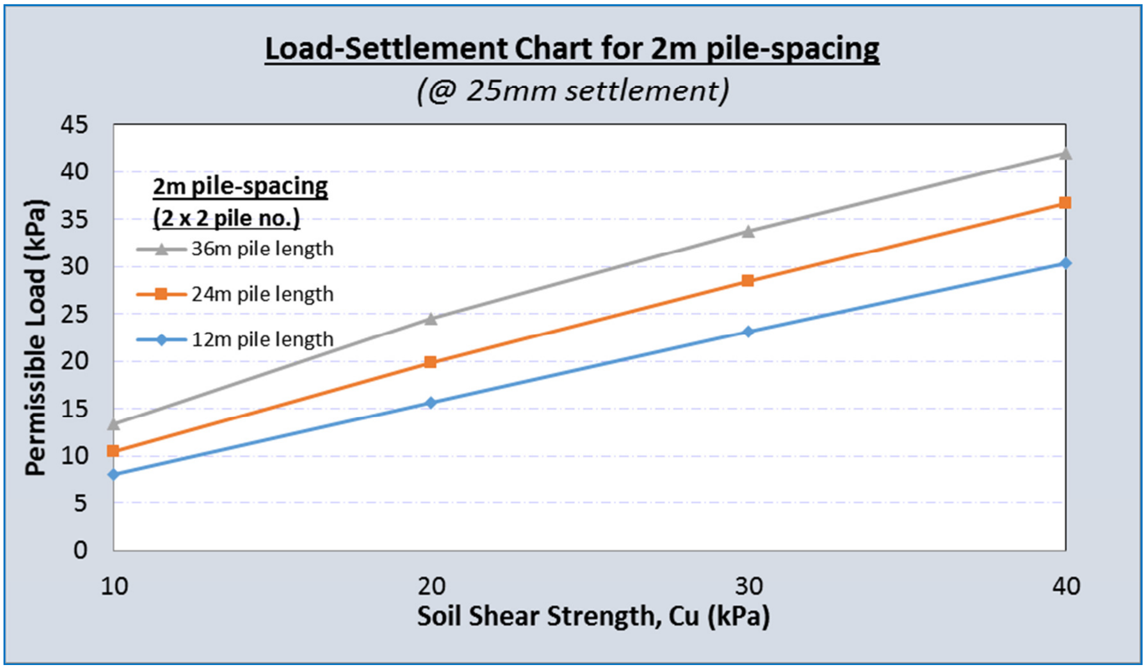

Figure 4.15.1: Permissible Bearing Load versus Undrained Shear Strength of Clay

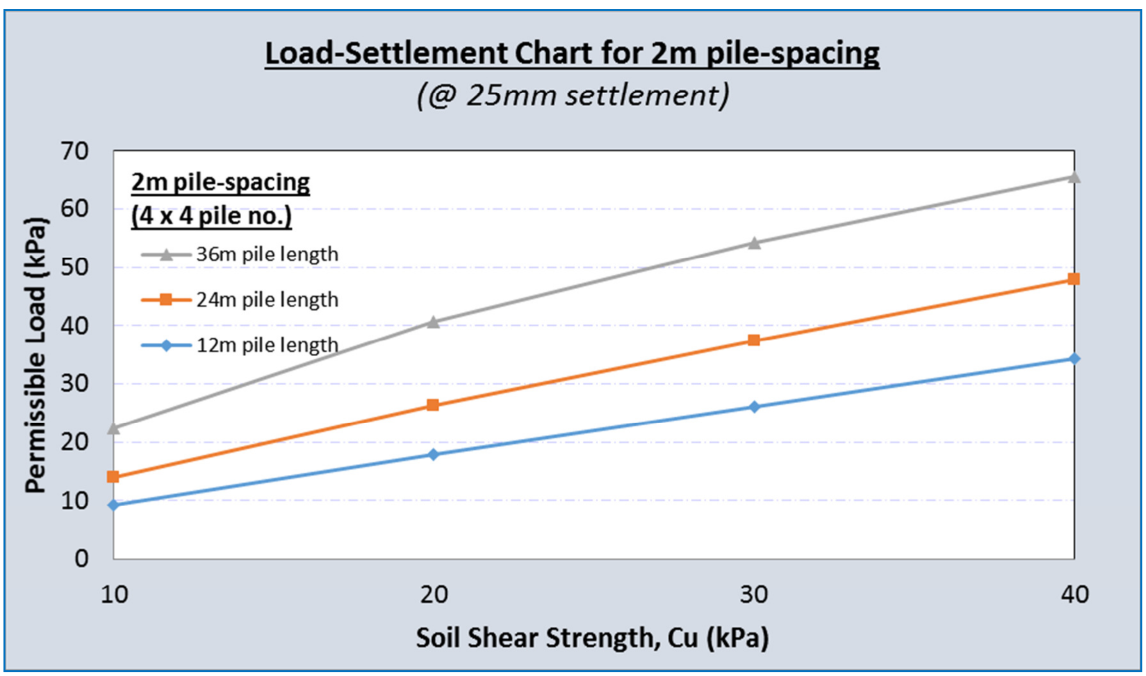

Figure 4.15.2: Permissible Bearing Load versus Undrained Shear Strength of Clay

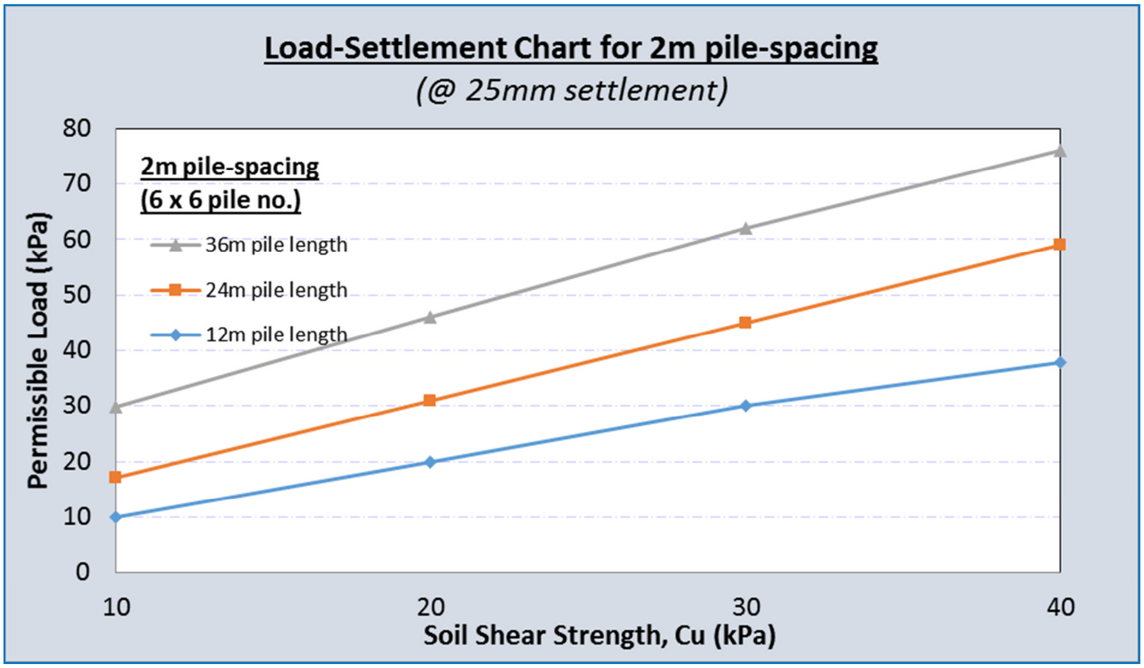

Figure 4.15.3: Permissible Bearing Load versus Undrained Shear Strength of Clay

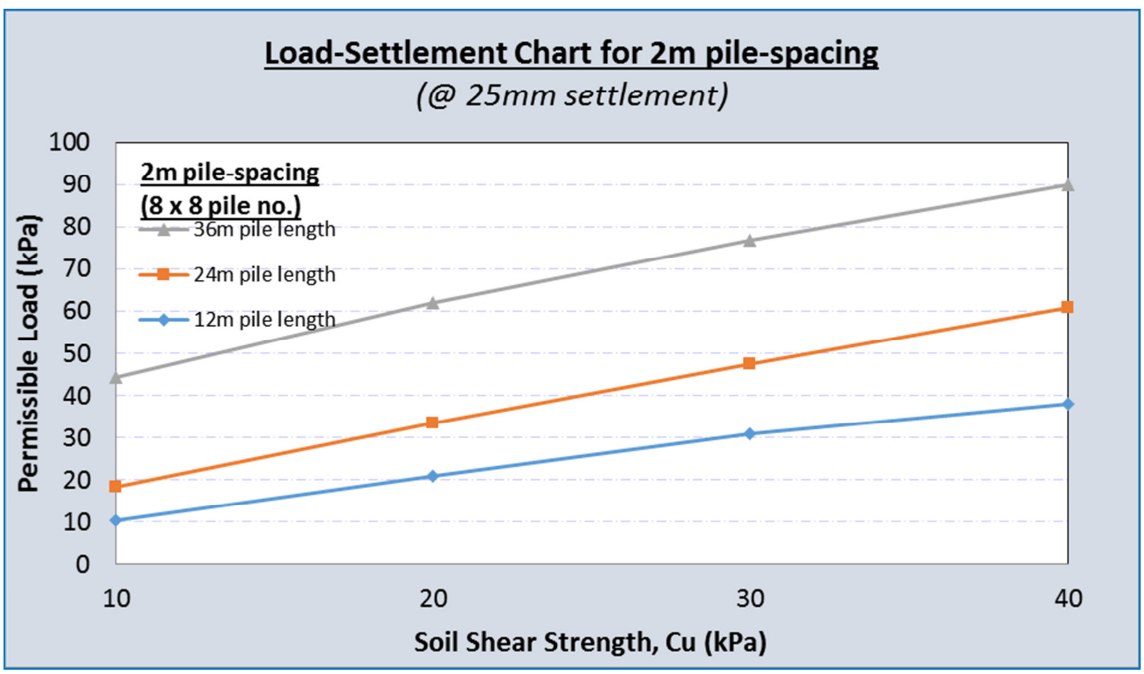

Figure 4.15.4: Permissible Bearing Load versus Undrained Shear Strength of Clay

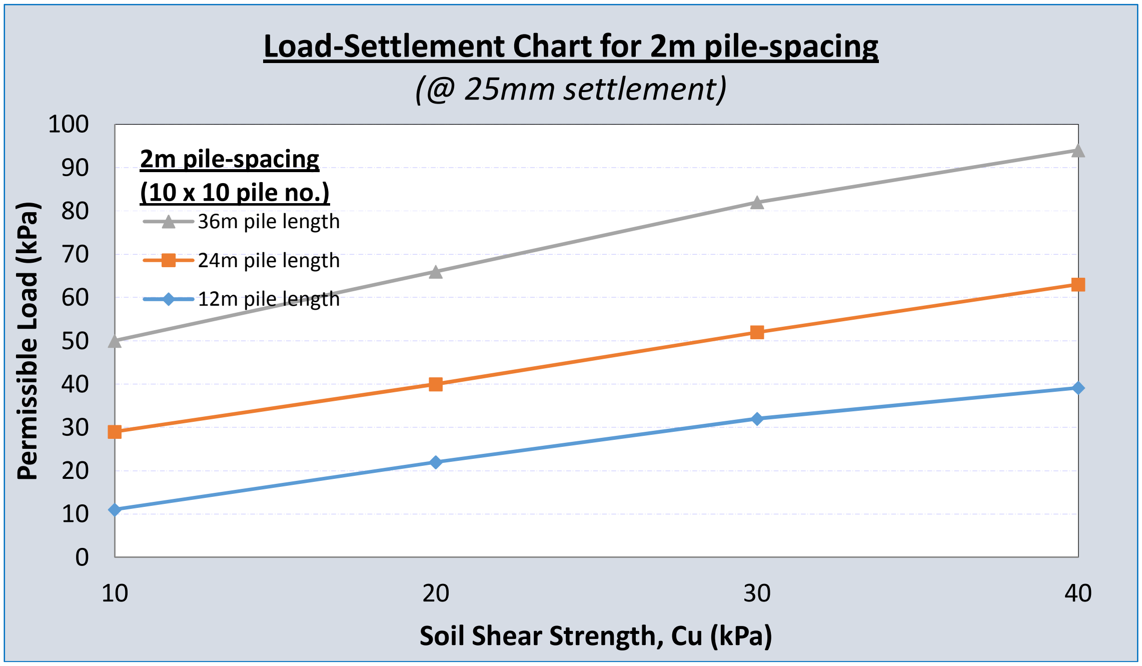

Figure 4.15.5: Permissible Bearing Load versus Undrained Shear Strength of Clay

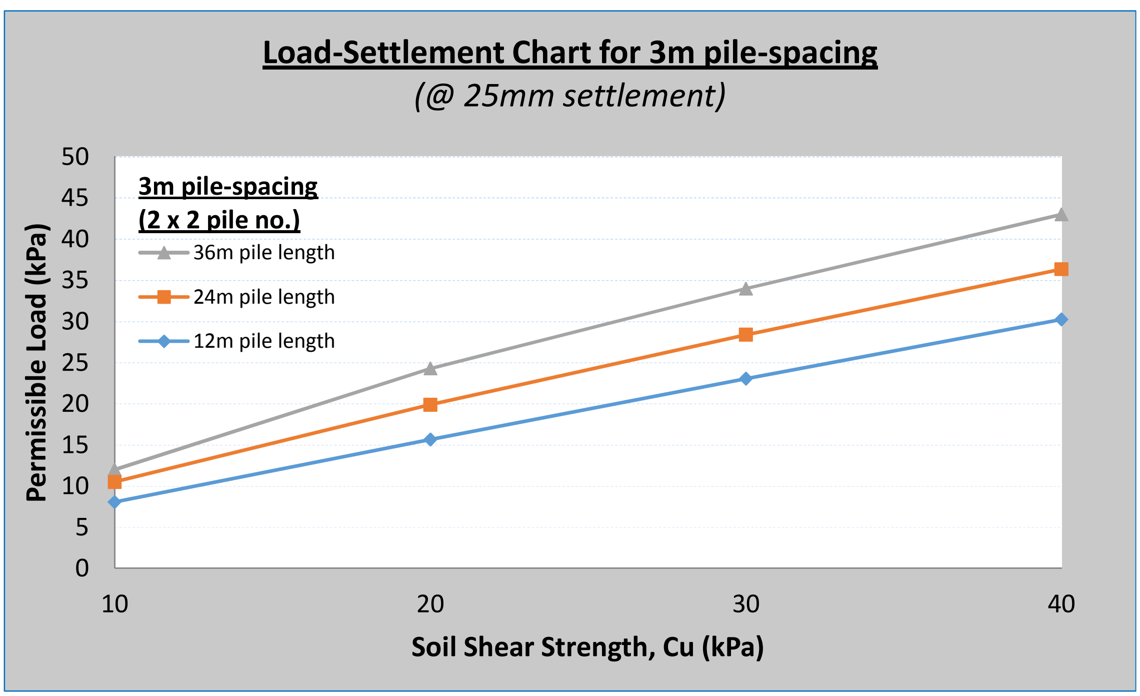

Figure 4.15.6: Permissible Bearing Load versus Undrained Shear Strength of Clay

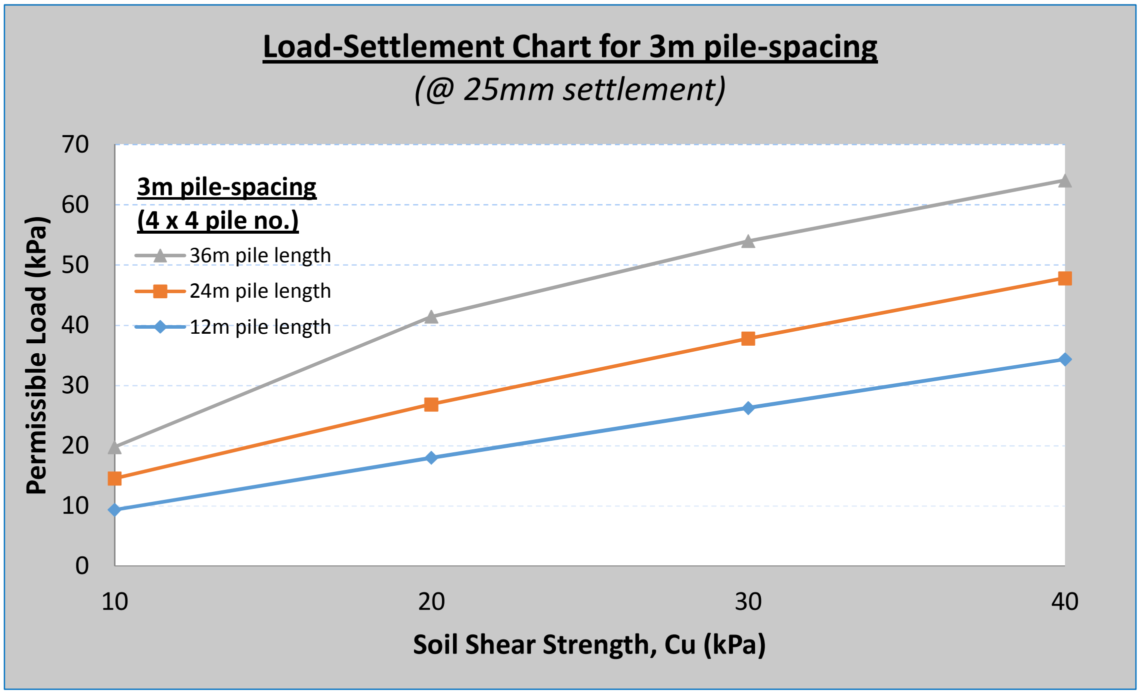

Figure 4.15.7: Permissible Bearing Load versus Undrained Shear Strength of Clay

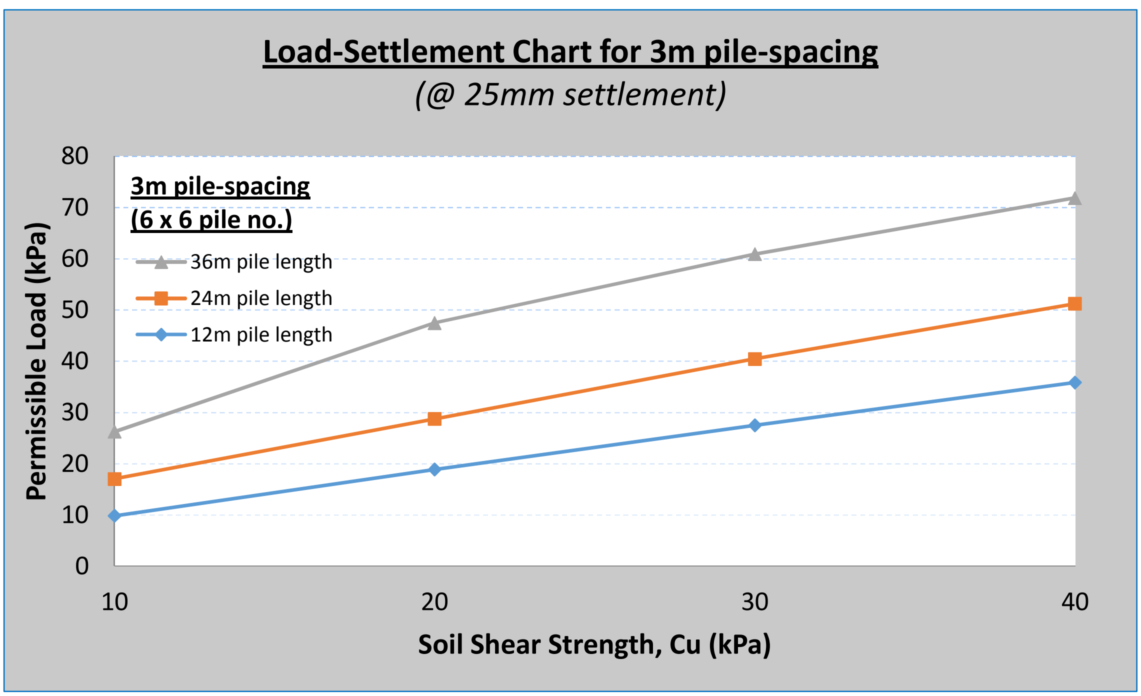

Figure 4.15.8: Permissible Bearing Load versus Undrained Shear Strength of Clay

4.16 Bearing Capacity of Large Piled-Raft Foundation

Figure 4.15.3 and Figure 4.15.8 revealed the significant of pile spacing and pile length on the bearing capacity of foundation. It is also notable that the patterns of bearing capacity are also very sensitive to any changes in the shear strength of soils. The conditions of the ground could cause some changes to the piled-raft rate of settlements and its behaviours too.

Further study into the details also illustrated that usually the pile base resistance is also often not fully mobilised during the short-term period. Even if the base resistance is mobilised, the distinction between the shaft and base resistance might not be exact. This has concurred with *Widjojo, A. and Fred, H. (2001)* reported for deep piles that the tip resistance generally is smaller as compared with the side resistance.

CHAPTER 5

DEVELOPMENT OF SIMPLIFIED DESIGN TECHNIQUES

CHAPTER 5: DEVELOPMENT OF SIMPLIFIED DESIGN TECHNIQUES

<u>Sections on Raft Foundation</u>

5.1 Development of Design Chart for Raft Foundation

A raft foundation design chart is developed and shown in Figure 5.1.1 to provide a quick reference guide for conceptual design stage and preliminary assessment work, project planning and cost estimation, safety and risk analysis study. It allows engineers quick access to estimate the likely bearing capacity of foundation against settlement based on raft foundation size, thickness and shear strength of soils at 25mm settlement.

Alternatively, it could also use to predict the permissible load on certain raft foundation to prevent causing of any unintentional “over-loading” to the structure embedding on the undrained soil during construction stage.

In all, this newly developed raft foundation design chart (Fig. 5.1.1) with bearing capacity of foundation provide pressure distribution with its highest and lowest threshold limits defined by the size of the raft foundations considered; 5m x 5m and 20m x 20m respectively.

Proposed design pedagogy with self-explanatory workflow (Fig. 6.2.1) for designing a raft foundation has been established together with systematic procedures and some worked examples to allow practice.

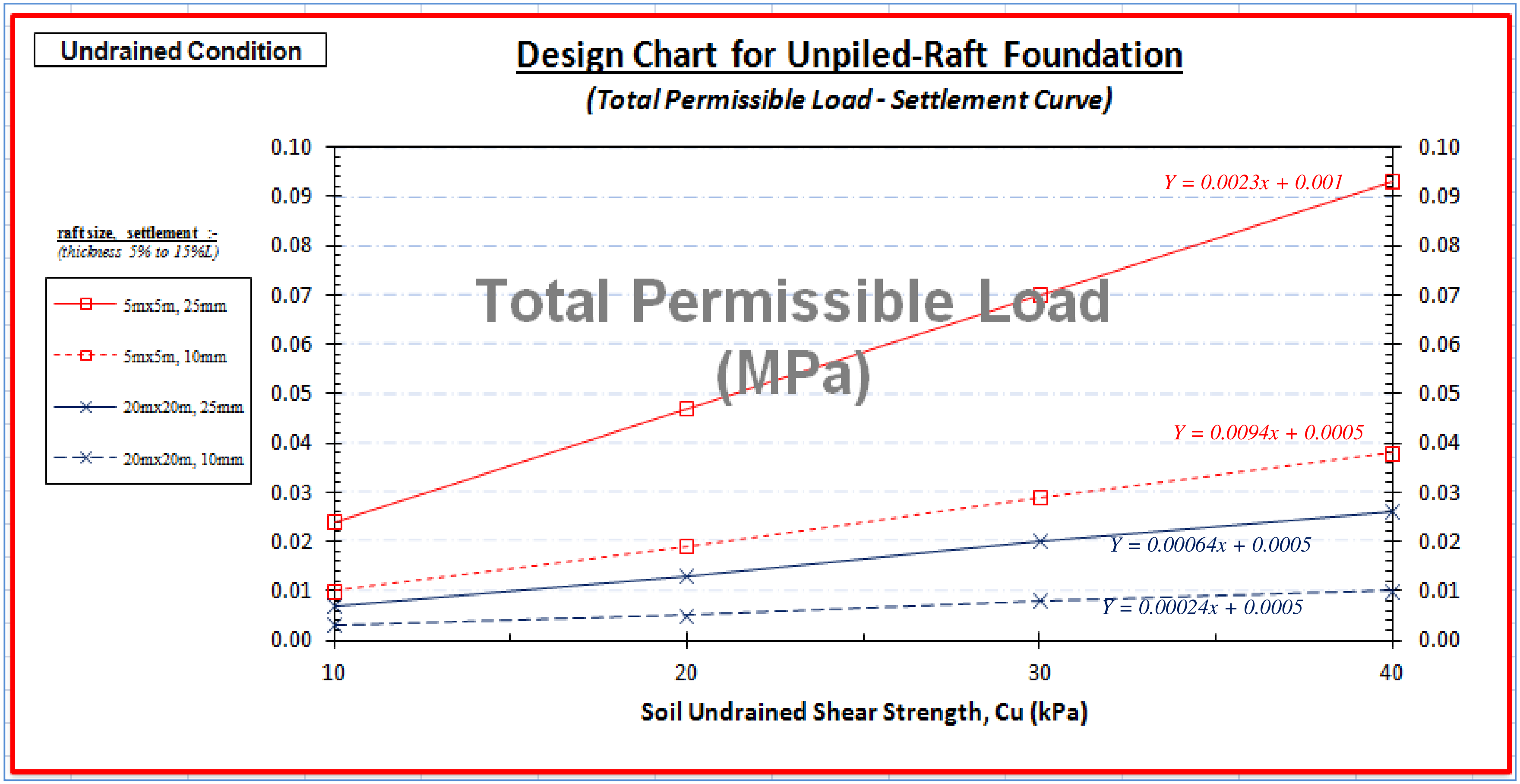

Figure 5.1.1: Design Chart for Raft Foundation

5.2 Evaluation of the New Design Chart for Raft Foundation

Following up with the numerical study done on the raft foundation, some elastic solutions are conducted to verify and evaluate the newly developed design chart shown in Figure 5.1.1.

On the study of the settlement at 25mm, it is noted that all bearing capacity against settlement behaviours has fallen within the elastic limit range. Thus, the theoretical elastic displacement calculation method usually used for the immediate settlement is proposed and used to evaluate the analysed results.

Adhering to *Christian and Carrier (1978)* proposal on the use of results by both *Giroud (1972)* and *Burland (1970)*, the average immediate vertical displacement under a flexible area carrying a uniform pressure *q* is given by:

$$S_i = (qB/E)\mu_0\mu_1$$

- Where μ_0 depends on the depth on the earth of embedment and μ_1 depends on the layer thickness and the shape of the loaded area.

- Values of the coefficients μ_0 and μ_1 for Poisson's ratio equal to 0.5 could be determined in Figure 5.2.1.

Comparisons on the short-term bearing capacity against settlement results between Plaxis 3D-FEM and theoretical methods using elastic displacement formula on immediate settlement are presented in some graphical forms in the two Figures (Fig. 5.2.2 & Fig. 5.2.3).

The Poisson ratio used in the theoretical calculation is based on fixed figure of 0.5.

On summary, comparison works between numerical and elastic solutions have proven the new design chart (Fig. 5.1.1) is convincing and the differences are less than 5% mainly due to soil-structure interaction effect of the 3D FEM modelling and the effective Poisson's ratio used in the analyses as explained in Para 3.6.

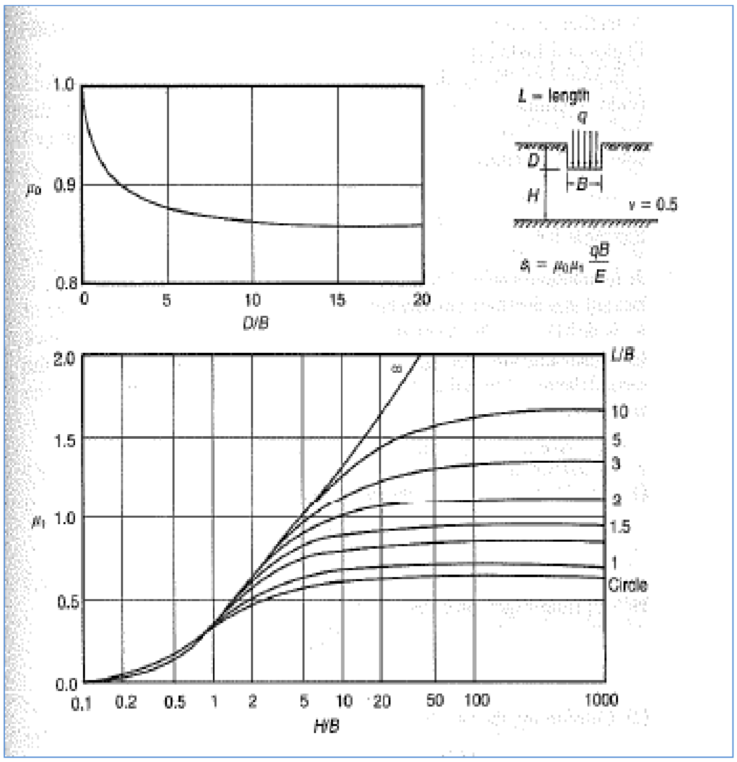

Figure 5.2.1: Coefficients μ_0 and μ_1
(Source from Craig, 1992)

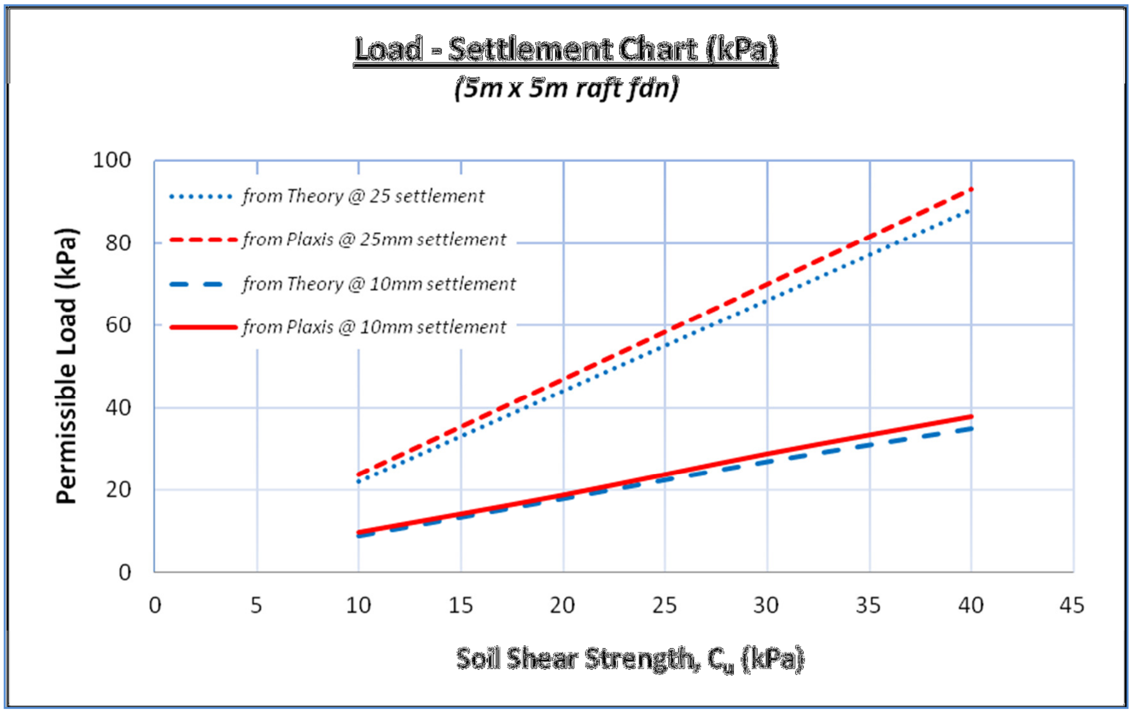

Figure 5.2.2: Permissible Bearing Load versus Undrained Shear Strength of Clay

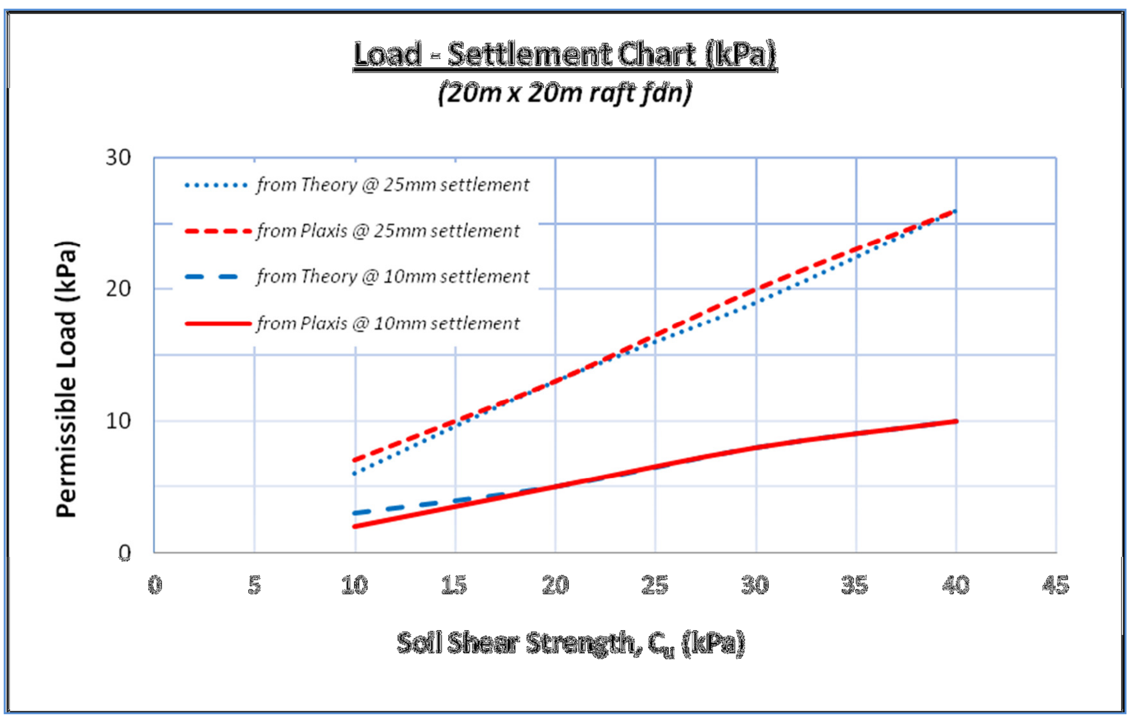

Figure 5.2.3: Permissible Bearing Load versus Undrained Shear Strength of Clay

Section on Piled-Raft Foundation

5.3 Determine the Significance of Raft in Piled-Raft Foundation

To determine contribution of the raft from the piled-raft foundation, the capacity of load bearing against settlement behaviours at 25mm settlement for both raft and piled-raft models are exported for detailed studies. The percentages of contribution from the raft are presented in the two figures (Fig. 5.3.1 & Fig. 5.3.2).

Generally, the significance of the raft contribution in a piled-raft foundation has manifested on wider pile-spacing piled-raft structure.

For piled-raft model with 2m pile-spacing at square grid arrangement, the contribution of the raft is almost constant even when the shear strength of soils increases. In fact, the percentage of it raft contribution has decreased significantly when the pile lengthened.

For piled-raft model with 3m pile-spacing at square grid arrangement, the contribution of the raft is more apparent comparing to the 2m piled-spacing arrangement with same total number of piles due to the former having wider soffit area between piles pressuring on the soft clay. However, increment on the raft's contribution is very mild even when increase in shear strength of the soils. In addition, the percentage of contribution decreases drastically as the pile length increases.

In summary, the significant factors of influence to increase the contribution of the raft in the piled-raft foundation are to having wider piles spacing arrangement, seconded by lengthening of the piles.

Small Piled-Raft Foundation

For small piled-raft foundation (5m x 5m), the four figures (Fig. 4.9.1, Fig. 4.9.2, Fig. 5.3.1 & 5.3.2) are all condensed further to develop into an integrated design chart to reflect bearing capacity of foundation as shown in Figure 5.4.1.

Medium Piled-Raft Foundation

For medium piled-raft foundation (10m x 10m), the the two figures (Fig. 4.12.1 & Fig. 4.12.2) are condensed together to develop into an integrated design chart to reflect bearing capacity of foundation as shown in Figure 5.4.2.

Large Piled-Raft Foundation

On large piled-raft foundation (20m x 20m), the two figures (Fig. 5.3.5 & Fig. 5.3.6) are condensed together to develop into an integrated design chart to reflect bearing capacity of foundation as shown in Figure 5.4.3.

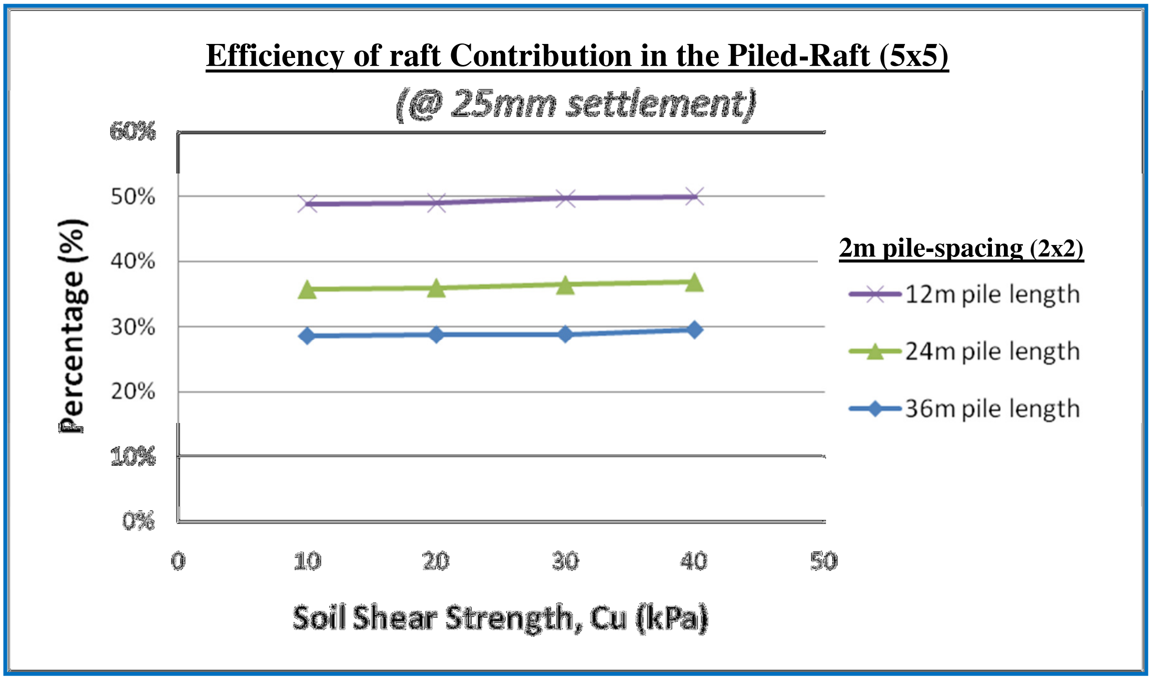

Figure 5.3.1: Efficiency of Raft Contribution

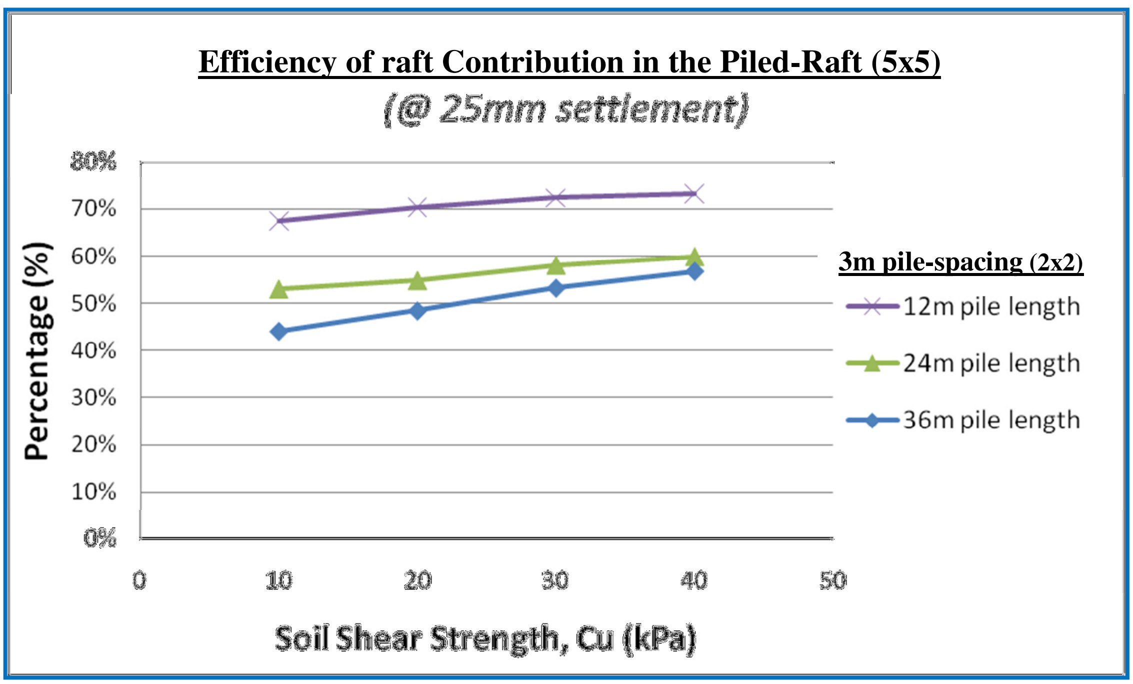

Figure 5.3.2: Efficiency of Raft Contribution

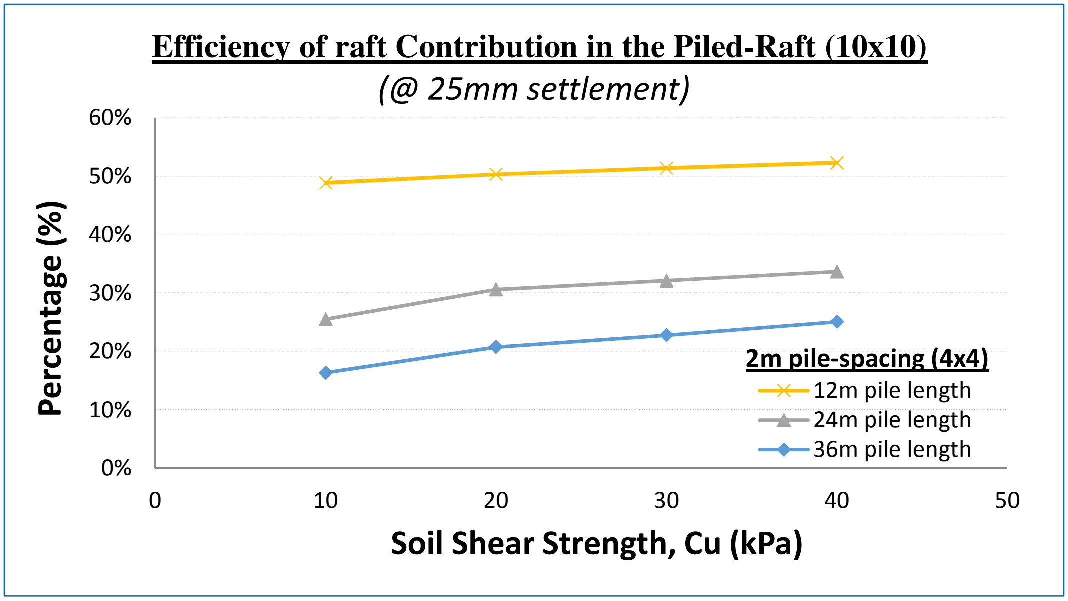

Figure 5.3.3: Efficiency of Raft Contribution

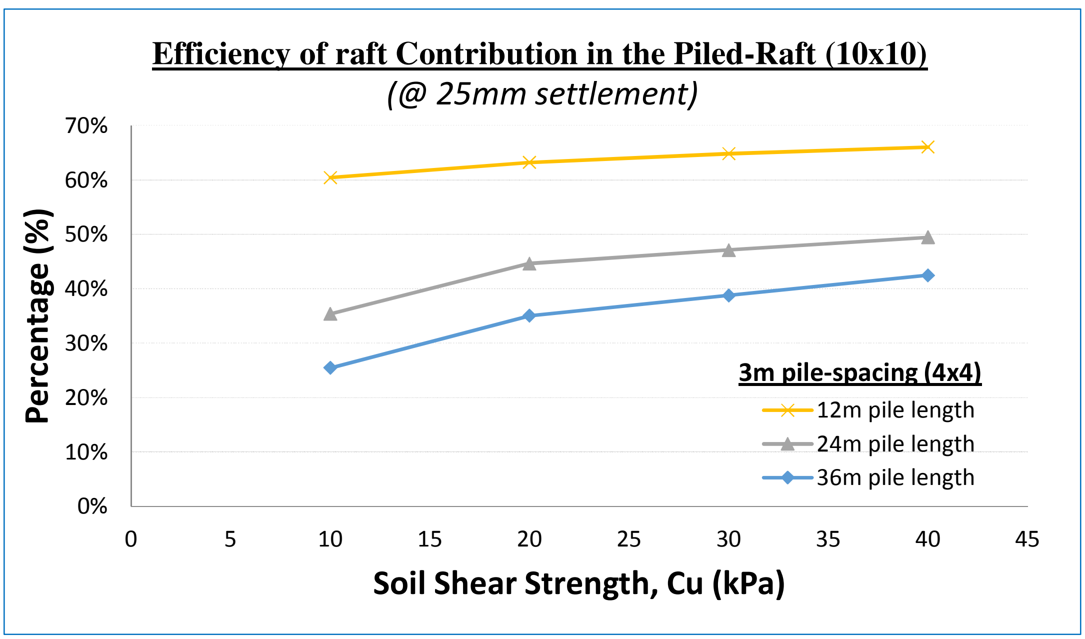

Figure 5.3.4: Efficiency of Raft Contribution

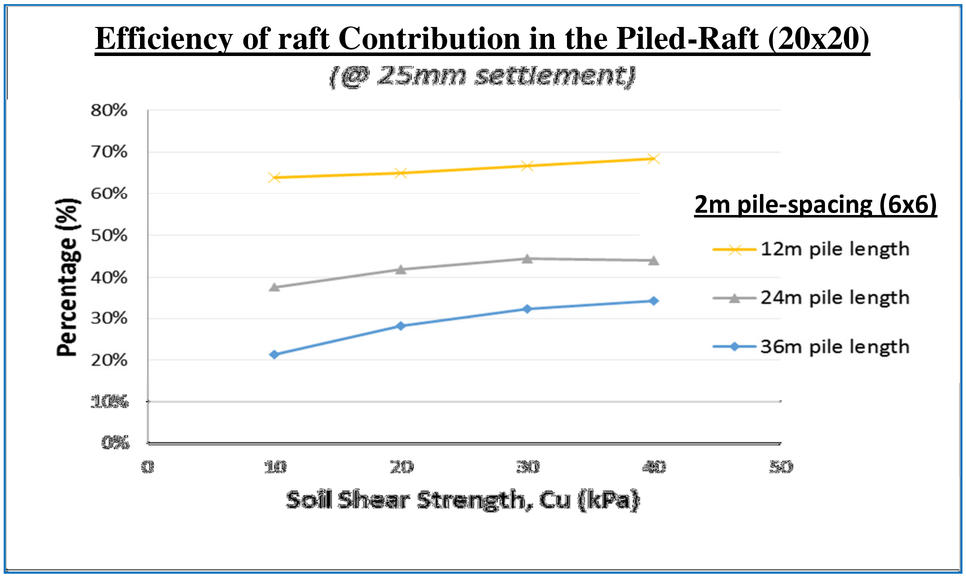

Figure 5.3.5: Efficiency of Raft Contribution

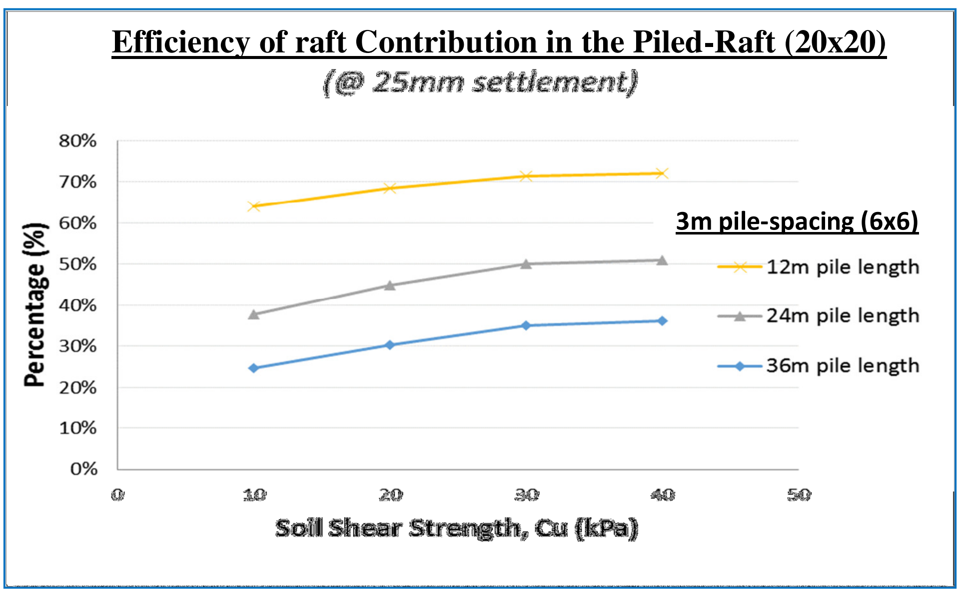

Figure 5.3.6: Efficiency of Raft Contribution

5.4 Development of Design Charts for Piled-Raft Foundation

The newly developed design charts on Figure 5.4.1, Figure 5.4.2 and Figure 5.4.3 offer an alternative to provide quick guides for conceptual design and preliminary assessment work, project planning and cost estimation, safety and risk analysis studies. It allow users to estimate what would be the likely bearing capacity against settlement behaviours of a small (5mx5m) to large (20m x 20m) piled-raft foundations based on the intended choice of foundation i.e. loadings, thickness of raft, spacing of piles, length of piles and shear strength of the soils. It could be used to predict permissible load at maximum 25mm settlement to prevent causing of any unintentional "over-loadings" on the soft clayey soil during construction stage.

In all, these newly developed piled-raft foundation design charts; total loads against settlement @ 25mm, offers a spectrum of bearing capacity against settlement behaviours ranging from 2m to 3m spacing of piles arrangement with different length of piles and various foundation sizes under different shear strength of clays at undrained soil conditions

Proposed self-explanatory design workflows with design pedagogies on the design of piled-raft foundation have been established together with step-by-step procedures and some worked examples are presented for learning purpose.

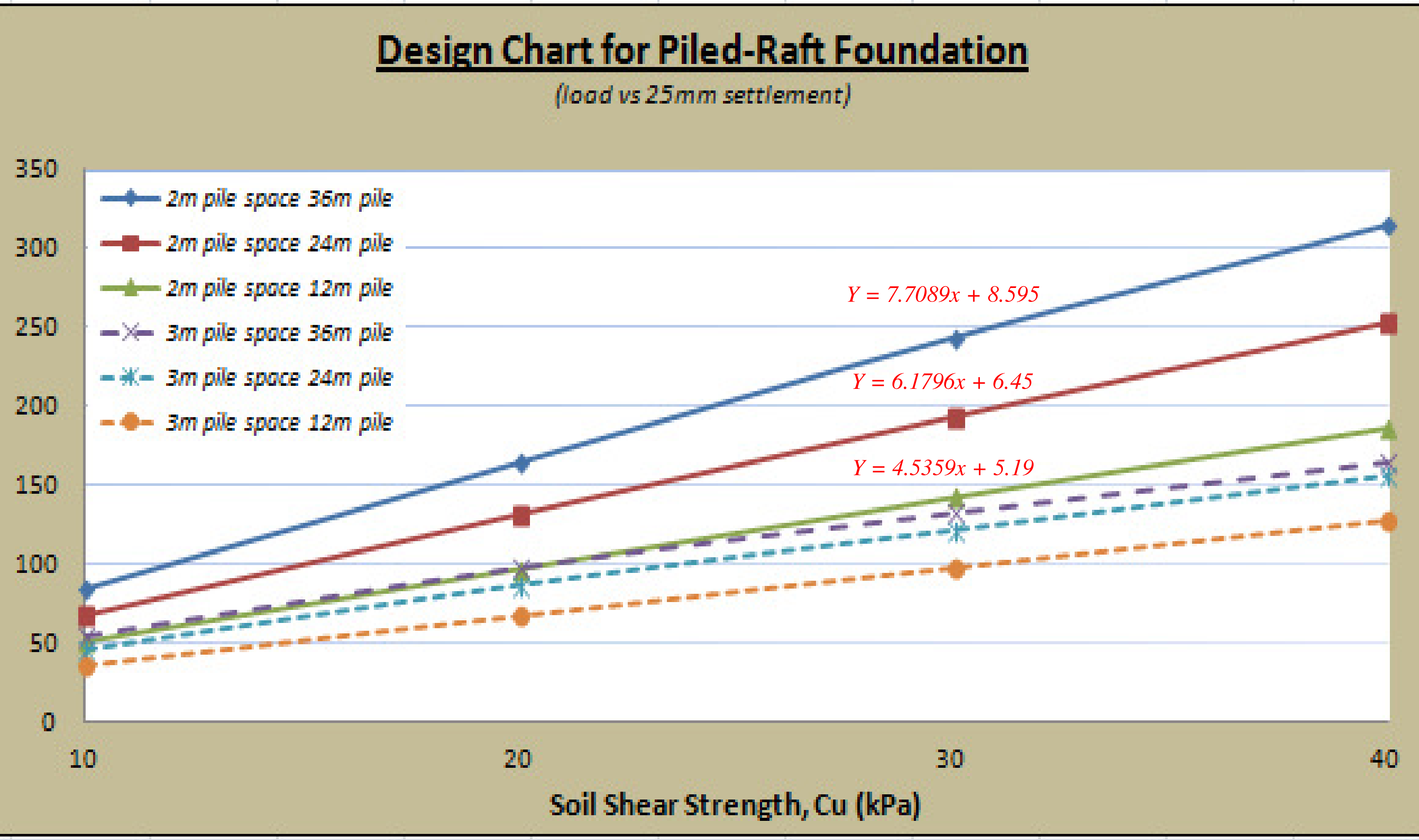

Figure 5.4.1: Design Chart for Small Piled-Raft Foundation

Pile Arrangement: 2x2

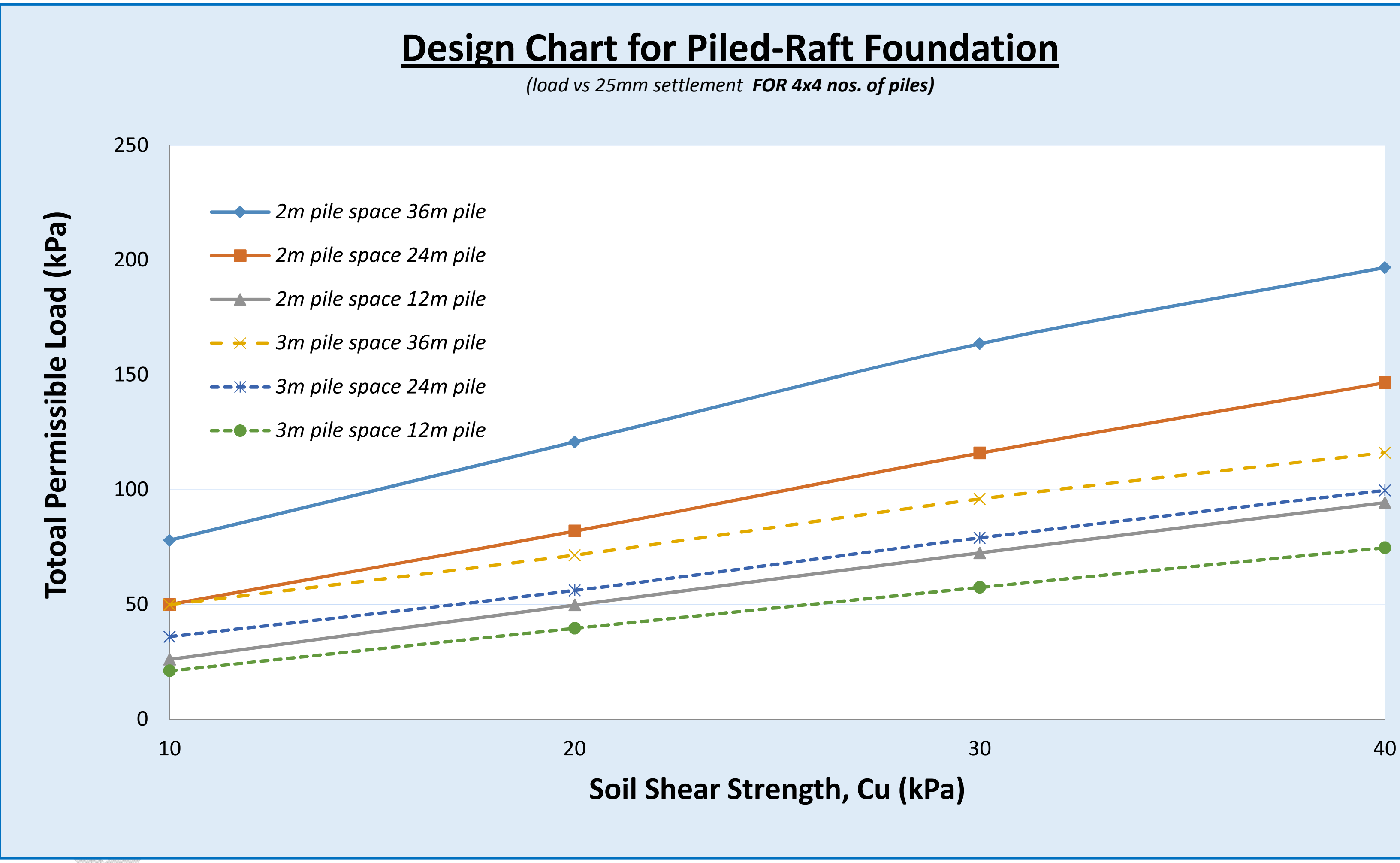

Figure 5.4.2: Design Chart for Medium Piled-Raft Foundation

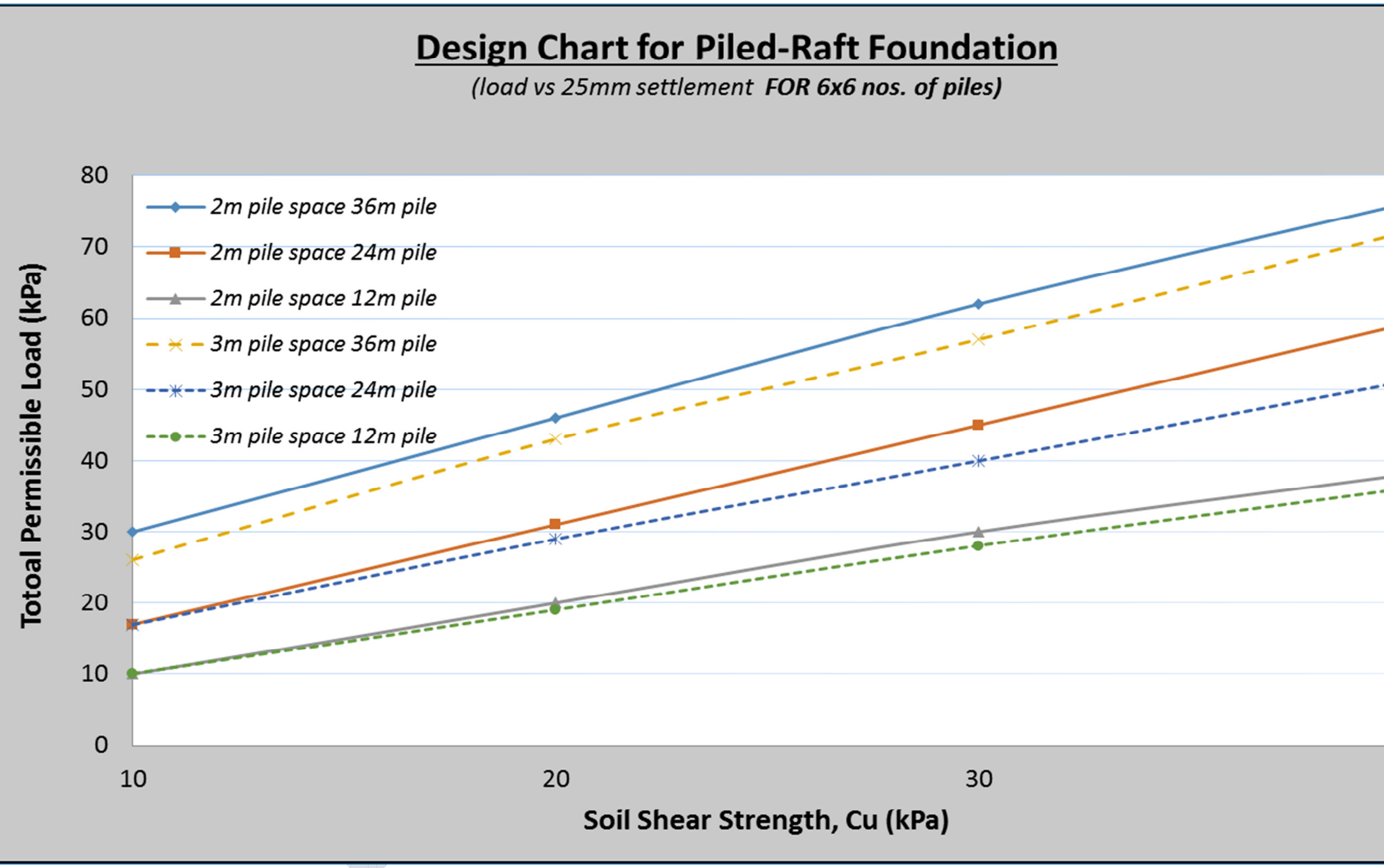

Figure 5.4.3: Design Chart for Large Piled-Raft Foundation

5.5 General formula to suit the research work

A general formula (Equation 7.2.1) which considered the contribution of the raft is used to evaluate the developed simplified design techniques. More details could be found in Para 7.2.

The bearing capacity against settlement behaviours calculated using this general formula is denoted as "general formula".

5.6 Evaluation on the Newly Developed Simplified Design Techniques

Following with the numerical studies done on the piled-raft foundations, an elastic solutions using elastic displacement method to calculate immediate settlements are launched to evaluate the following :-

i) The newly developed design charts for Figure. 4.2.4, Figure. 4.9.1, Figure. 4.12.1 & Figure. 4.15.5),

ii) The newly developed design Table 7.2.1.

Existing Equivalent Raft Method Theory - *by Christian & Carrier (1978)*

Theoretically, settlement of a pile group in clay could be estimated by assuming the total load carried by an "equivalent raft" located at a depth of *2L/3* where *L* is the length of the piles. It may be assumed, as shown in Figure 5.6.1, that the load is spreaded from the perimeter of the group at a slope of 1 horizontal to 4 vertical to allow for that part of the load transferred to the soil by skin friction. Thus, the average immediate vertical displacement (S_i) under a flexible area carrying a uniform pressure q is given by:

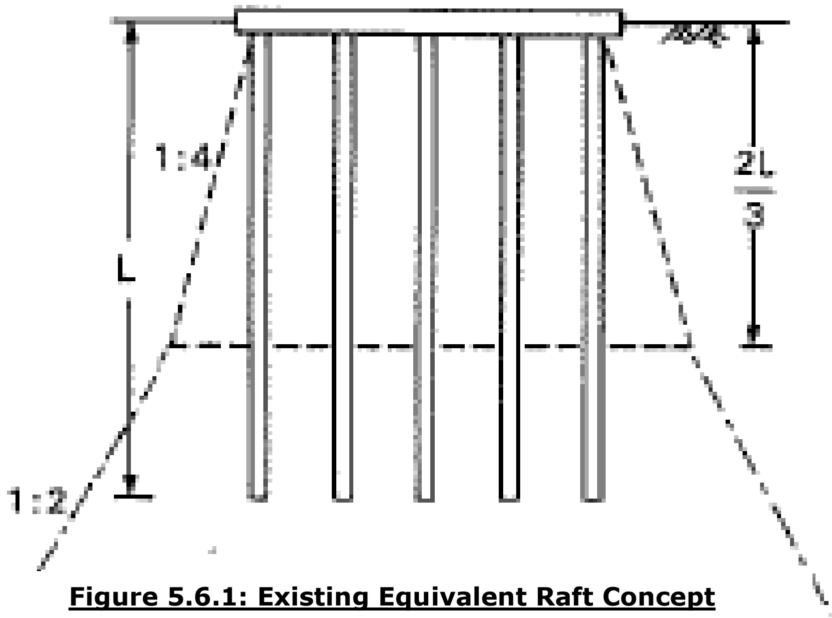

Figure 5.6.1: Existing Equivalent Raft Concept

(Source from R.F. Craig, 1992)

$S_i = (qB/E)\mu_0\mu_1$

- Where μ_0 depends on the depth on the earth of embedment and μ_1 depends on the layer thickness and the shape of the loaded area.

- Values of the coefficients μ_0 and μ_1 for Poisson's ratio equal to 0.5 are given in Figure 5.2.1.

- B is the width of equivalent raft located at 2L/3 below the top of the piles

The General Formula Theory

The general formula (Equation 7.2.1) for calculating the foundation bearing capacity took into consideration the contribution of the raft has proven to be more effective than the existing equivalent raft's elastic solution when comparing with the numerical studies done with the soil-raft-pile interactions effect in the rigorous 3D FEM modelling.

The average immediate vertical displacement (S_i) for the general formula under a flexible area carrying a uniform pressure q is given by:

$$S_i = (qB/E)\mu_0\mu_1 * (B_e/B)$$

- Where μ_0 depends on the depth on the earth of embedment and μ_1 depends on the layer thickness and the shape of the loaded area.
- Values of the coefficients μ_0 and μ_1 for Poisson's ratio equal to 0.5 are given in Fig. 5.2.1.
- B is the width of equivalent raft located at 2L/3 below the top of the piles
- B_e is the distance between 2 outermost piles

Evaluation of the Piled-Raft Foundation Design Techniques

Small Piled-Raft Foundation

Comparison on the short-term bearing capacity against settlement results between the 3D Plaxis and both general formula and elastic calculation are presented in the three figures (Fig 5.6.2 to Fig 5.6.3).

The Poisson's ratio used in theoretical calculation is based on fixed figure of 0.5. In addition, the elastic displacement formula for Figure 5.6.1 does not take into consideration the effects of both spacing of and length of the piles.

From the three figures (Fig 5.6.2 to Fig 5.6.4), the bearing capacity against settlement behaviours have presented a common pattern – linear incremental trend. The numerical results using the 3-D FEM Plaxis are much higher compared to its' elastic solutions followed by the general formula mainly due to the rigorous soil-structure interaction effects in the 3-D FEM modelling and the effective Poisson's ratio used in the analyses work.

The general formula is found to be more efficient when comparing with the elastic solution using elastic displacement formula (Fig. 5.6.2 to Fig. 5.6.4). The numerical results using the 3-D FEM Plaxis are averagely 15% higher compared to the general formula (Equation 7.2.1), and 65% higher compared to the elastic solutions.

In summary, the numerical results from the developed design chart (Fig. 4.9.1) are closed to the general formula (Equation 7.2.1) that takes into consideration of the raft contribution.

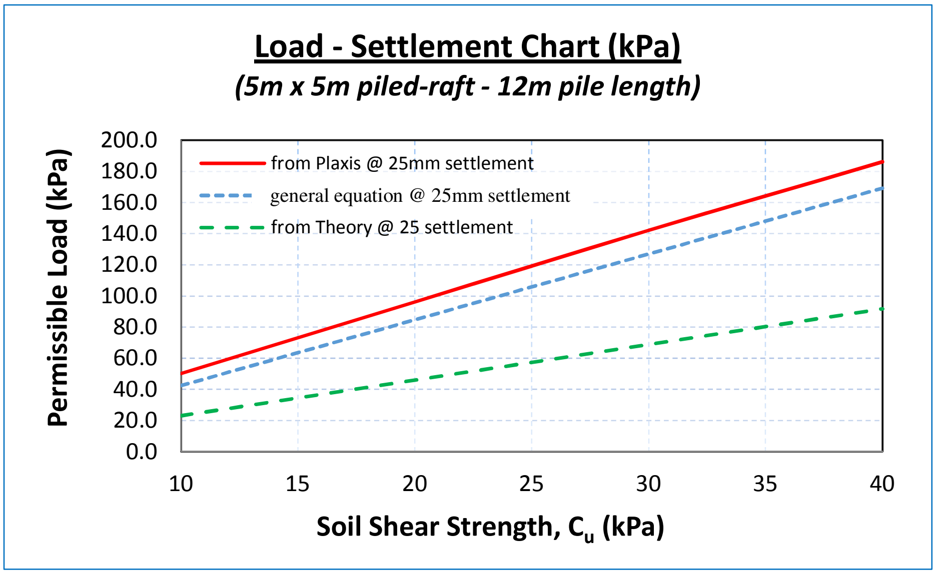

Figure 5.6.2: Permissible Bearing Load versus Undrained Shear Strength of Clay

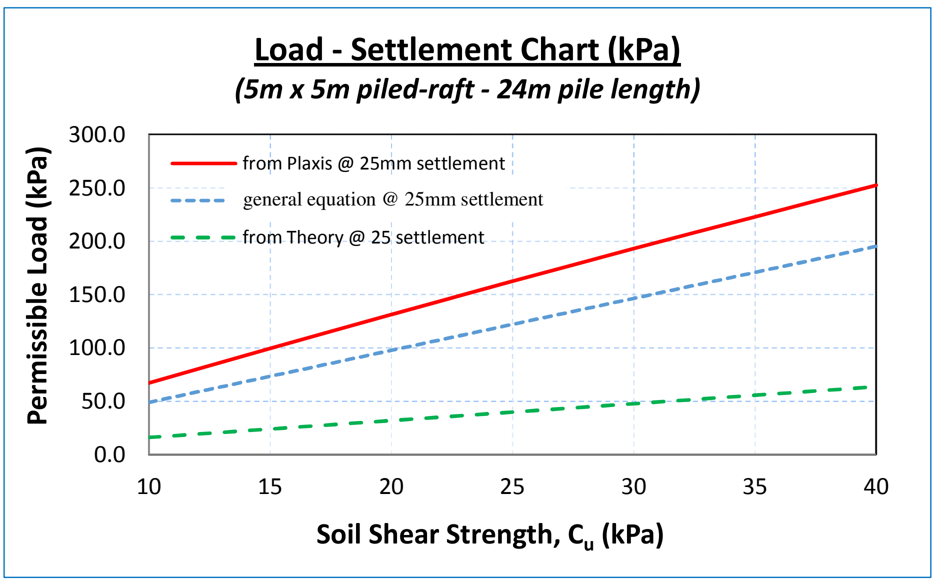

Figure 5.6.3: Permissible Bearing Load versus Undrained Shear Strength of Clay

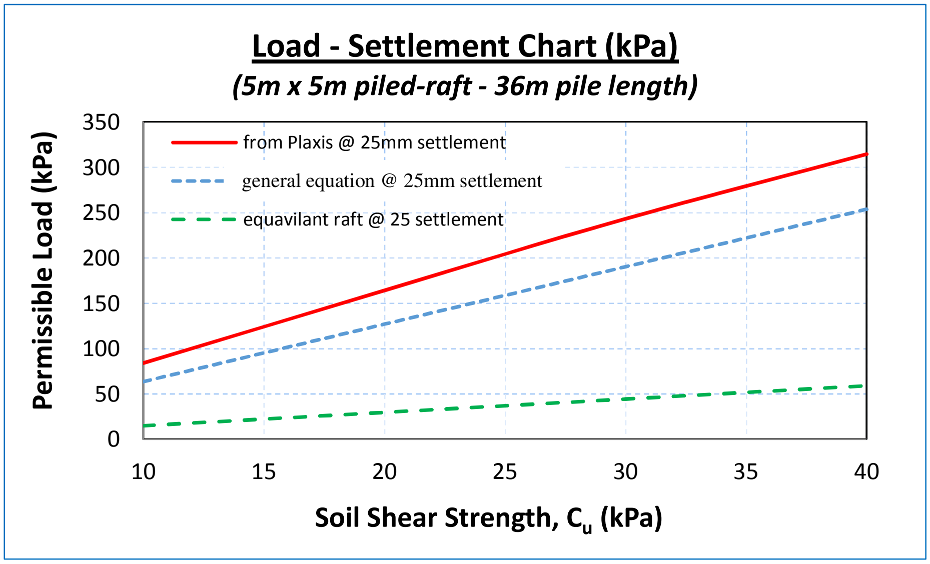

Figure 5.6.4: Permissible Bearing Load versus Undrained Shear Strength of Clay

<u>Medium Piled-Raft Foundation</u>

Comparison on the short-term bearing capacity against settlement results between the 3D Plaxis and both general formula and elastic solutions are presented in the three figures (Fig 5.6.5 to Fig 5.6.7).

The Poisson's ratio used in the elastic solutions based on fixed figure of 0.5. The elastic displacement formula for figure 5.6.1 does not take into consideration the effects of both spacing and length of the piles.

From the three figures (Fig 5.6.5 to Fig 5.6.7), the bearing capacity against settlement behaviours have presented a common pattern – linear incremental trend. The numerical results using the 3-D FEM Plaxis are much higher compared to its' elastic solution followed by the general formula mainly due to the rigorous soil-structure interaction effects in the 3-D FEM modelling and the effective Poisson's ratio used in the analyses works.

The general formula is found to be more efficient when comparing with the elastic solutions (Figure 5.6.5 to Figure 5.6.7). The numerical results using the 3-D FEM Plaxis are averagely 20% higher compared to the general formula (Equation 7.2.1), and 60% higher compared to the elastic solutions.

In summary, the numerical results from the developed design chart (Fig. 4.12.1) are closed to the general formula (Equation 7.2.1) that takes into consideration of the raft contribution.

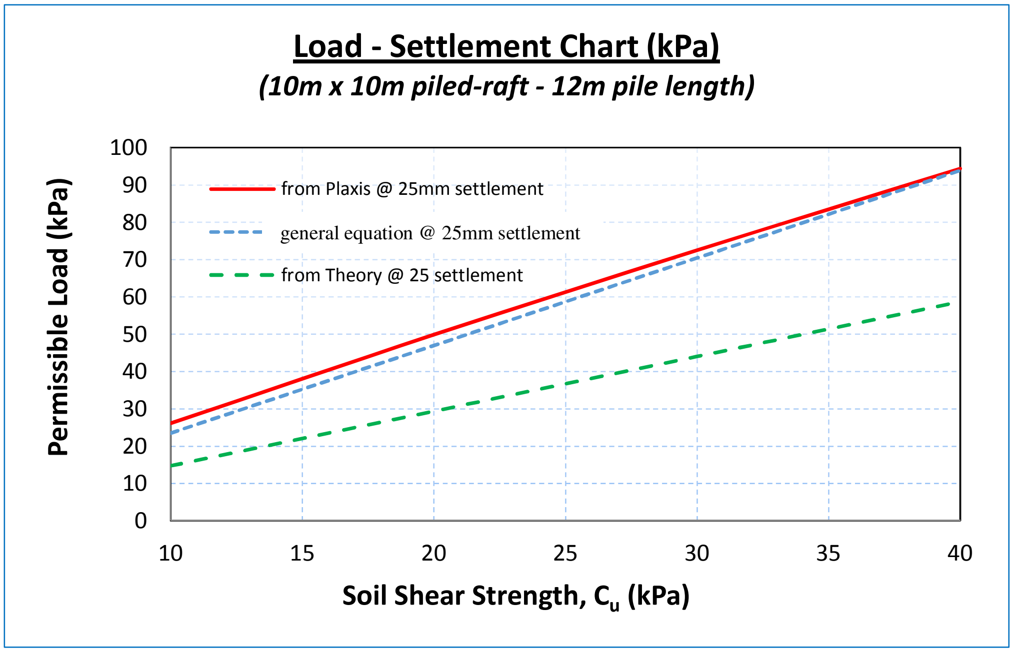

Figure 5.6.5: Permissible Bearing Load versus Undrained Shear Strength of Clay

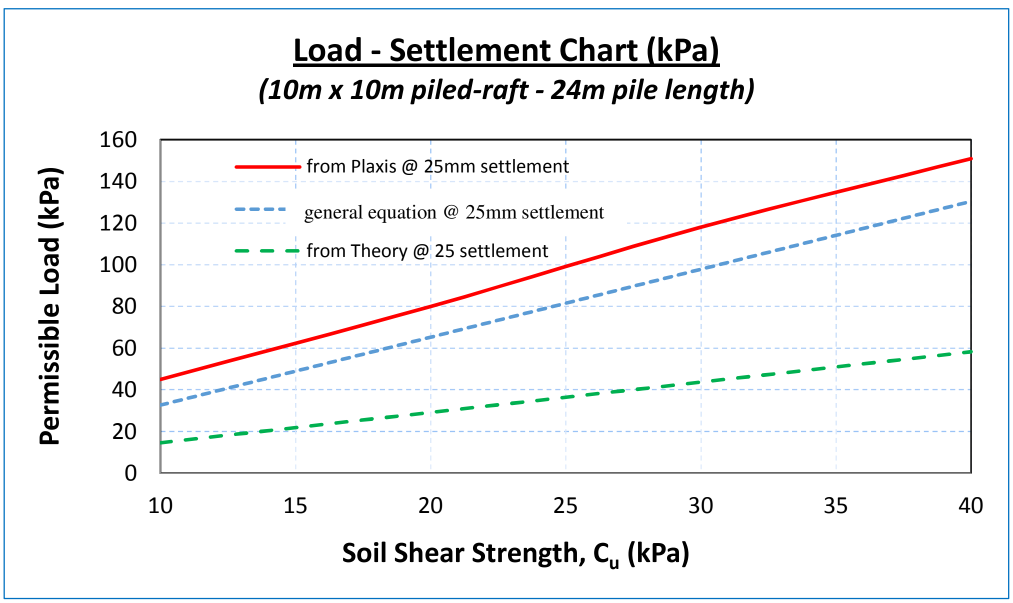

Figure 5.6.6: Permissible Bearing Load versus Undrained Shear Strength of Clay

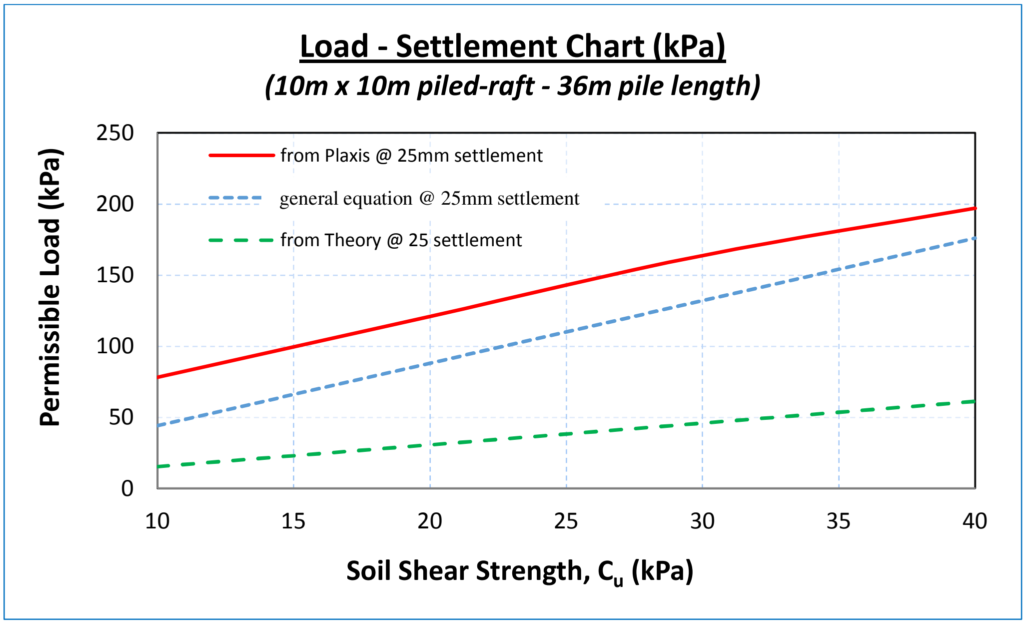

Figure 5.6.7: Permissible Bearing Load versus Undrained Shear Strength of Clay

Large Piled-Raft Foundation

Comparison on the short-term bearing capacity against settlement results between the 3D Plaxis and both general formula and elastic solutions are presented in the three figures (Fig 5.6.8 to Fig 5.6.10).

The Poisson's ratio used in elastic calculation is based on fixed figure of 0.5. The elastic displacement formula for Figure 5.6.1 does not takes into consideration the effects of both spacing and length of the piles.

From the three figures (Fig 5.6.8 to Fig 5.6.10), the bearing capacity against settlement behaviours have presented a common pattern – linear incremental trend. The numerical results using the 3-D FEM Plaxis are much higher compared to its' elastic solution followed by the general formula mainly due to the rigorous soil-structure interaction effects in the 3-D FEM modelling and the effective Poisson's ratio used in the analyses work.

The general formula is found to be more efficient when comparing with the elastic solution using elastic displacement formula (Figure 5.6.8 to Figure 5.6.10). The numerical results using the 3-D FEM Plaxis are averagely 15% higher compared to the general formula (Equation 7.2.1), and 50% higher compared to the elastic solutions.

In summary, the numerical results from the developed design chart (Fig. 4.15.5) are closed to the general formula (Equation 7.2.1) that takes into consideration of the raft contribution.

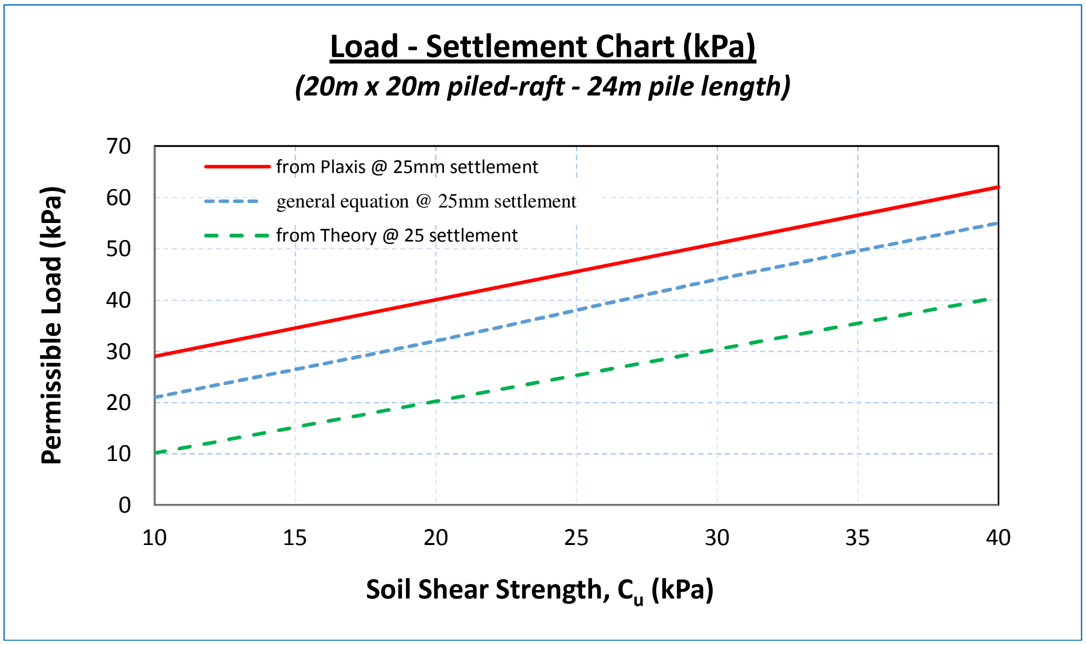

Figure 5.6.8: Permissible Bearing Load versus Undrained Shear Strength of Clay

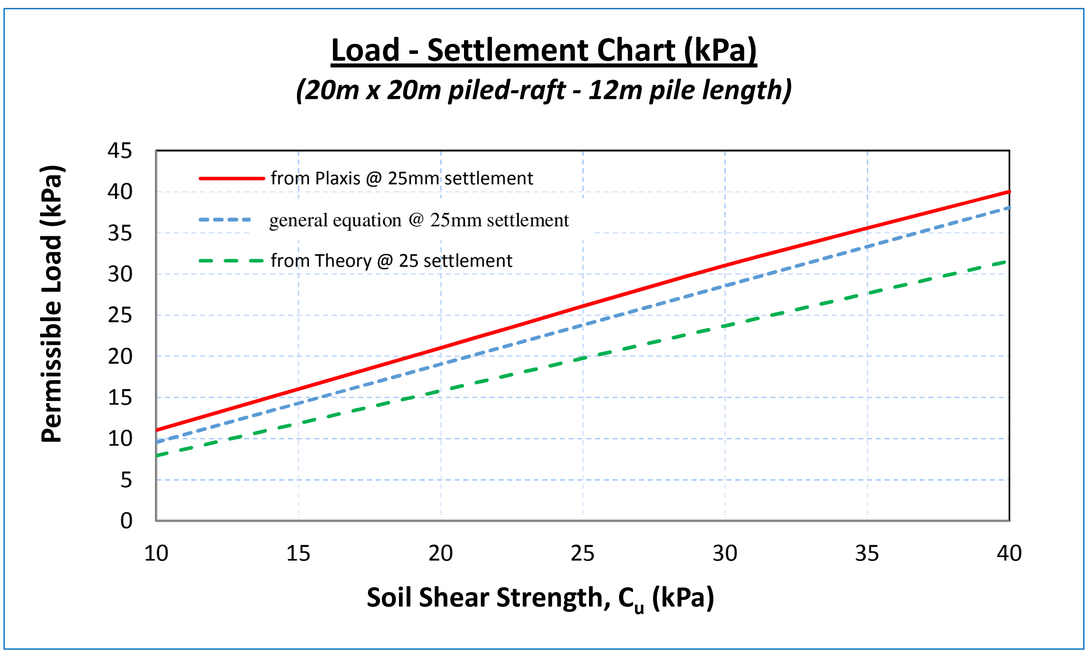

Figure 5.6.9: Permissible Bearing Load versus Undrained Shear Strength of Clay

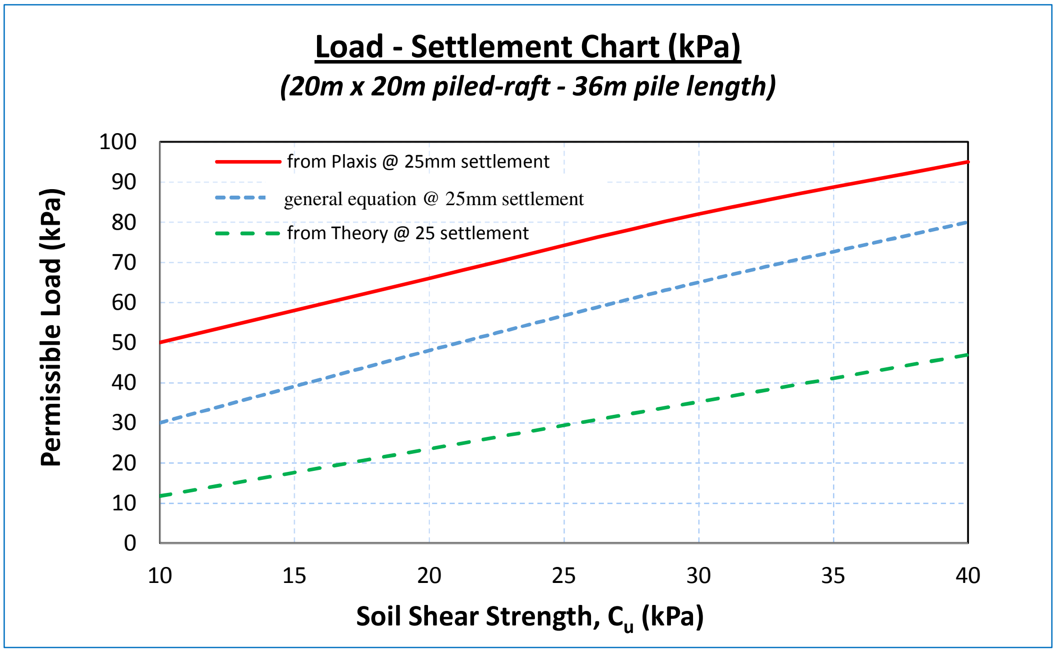

Figure 5.6.10: Permissible Bearing Load versus Undrained Shear Strength of Clay

5.7 Development of Design Table

To develop a versatile design table on bearing capacities for both raft and piled raft foundation designs, the four figures (Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5), are further consolidated, integrated and presented in Design Table 7.2.1.

The Design Table 7.2.1 presents the total permissible load for the both the raft and piled-raft foundations. Interpolation works are permissible so long; they are within the limits e.g. raft foundation to be from 5m x 5m to 20m x 20m, 2m pile spacing, and piled-raft foundation from 5m x 5m to 20m x 20m with maximum pile length of up to 36m deep.

5.8 Benchmarking the Newly Developed Simplified Design Techniques against Published References

The developed simplified design technique (Table 7.2.1) are benchmarked against some established case studies for reliability and efficiency. Two recent published case studies found quite similar to my research work are selected and used for the demonstrations (Case Study 1 & Case Study 2).

<u>Case study 1</u>

This comprehensive parametric study was performed on a 5m x 5m foundation with 12m pile length embedded on 8.3m thick clayey soil overlying layer fine sand to gravel with maximum thickness of 11.7m.

The case study is more similar to my research work compared to the other case study based on the soil profile and the structural configuration.

Methods	Bearing capacity at 25mm settlement	Remarks
Design Table 7.2.1 **After normalising the E.*	***46.7KPa**	Main reasons attributed to the small different in results are due to the following different parameters used: i. the Young's Modulus (E) of soil used in the Design Table is 300Cu kPa i.e. 3.9MPa and *Gopinath et al* is 6.5MPa; ii. Density of the soil used on the Design Table is 16kN/m^3 and *Gopinath et. al.* is 17.7kN/m^3; iii. Pile size used in the Design Table is 0.25mx0.25m and *Gopinath et. al.* is 0.3m diameter.
Gopinath et. al. (2010) Numerical Modelling of Piled Raft Foundation in Soft Clays Indian Geotechnical Conference – GEO*trendz*, Dec 2010. *[Figure 4: Load Settlement Curve for Different Pile Length (pile length = 6m)]*	**50kPa**	

<u>Table 5.8.1: Case Study 1 - Summary of Results at 25mm Settlement</u>

<u>Case study 2</u>

Methods	Bearing capacity at 32mm settlement	Remarks
Design Table 7.2.1 **After normalising the E.*	***159kPa**	Main reasons attributed to the different in results are due to the following different parameters used: i. The Young's Modulus (*E*) of soil used in the Design Table is 300Cu kPa and *Poulos et. al.* is 20MPa; ii. The Young's Modulus (*E*) of raft and pile used in the Design Table is 26MPa and *Poulos et. al.* is 30MPa; iii. The spacing of pile used in Design Table is 2m and Poulos et. al. is 4m; iv. Pile size used in the Design Table is 0.25mx0.25m and *Poulos et al* is 0.5m diameter.
Poulos, H.G. et. al. (1997) Comparison of some methods for analysis of piled rafts. Proc. 14th Int. Conf. Soil Mech. Foundation Engineering, Hamburg, 1997, Vol.2, pp1119-1124. *[Result from F.E. Ta and Small bearing capacity at 32mm is 200kPa.]*	**200kPa**	

In summary, it could be seen that the bearing capacities which include the contribution of the raft obtained from the developed simplified design technique are below the case studies. These demonstrations helped to reflect safety factor is on the acceptable range for the developed simplified method for preliminary design use.

Finite element method has been well accepted to be used to model piled-raft foundation. It is potentially the most accurate numerical methods available for piled-raft foundation analyses, although it is very time-consuming to set-up and run *(Poulos (2001b))*. The developed simplified design technique provide closer values to the FEM results compared to elastic solutions. This would allow engineers who cannot afford to do FE analysis to use this simplified method for preliminary design since it provide better results than the elastic solution.

These demonstrations helped to prove the efficiency of the newly developed simplified design techniques for preliminary design of piled-raft foundation at undrained soil conditions which reduce time and manpower contribution.

CHAPTER 6

GUIDELINES ON
NEW DESIGN TECHNIQUES

CHAPTER 6: GUIDELINES ON NEW DESIGN TECHNIQUES

6.1 Introduction

This chapter cover the guidelines and use of the newly developed simplified design techniques for raft and piled-raft foundation design:-

i) Design charts (Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5);

ii) Design table (Table 7.2.1).

The developed design pedagogies come with self-explanatory design workflows. The design requirements and guides leading to the complete design of the foundations have complied with the Code of Practice for Foundations.

<u>Limitations</u>

The design charts and table are ideal for immediate settlement of foundation of not more than 25mm. Interpolation works are permissible so long as they are within the limits e.g. maximum piled length is up to 36m, shear strength of soils up to 100kPa, piles are at 2m spacing.

6.2 Proposed Design Pedagogy for Raft Foundation

Assumption: The raft structure foundation is applied with uniformly distributed loads.

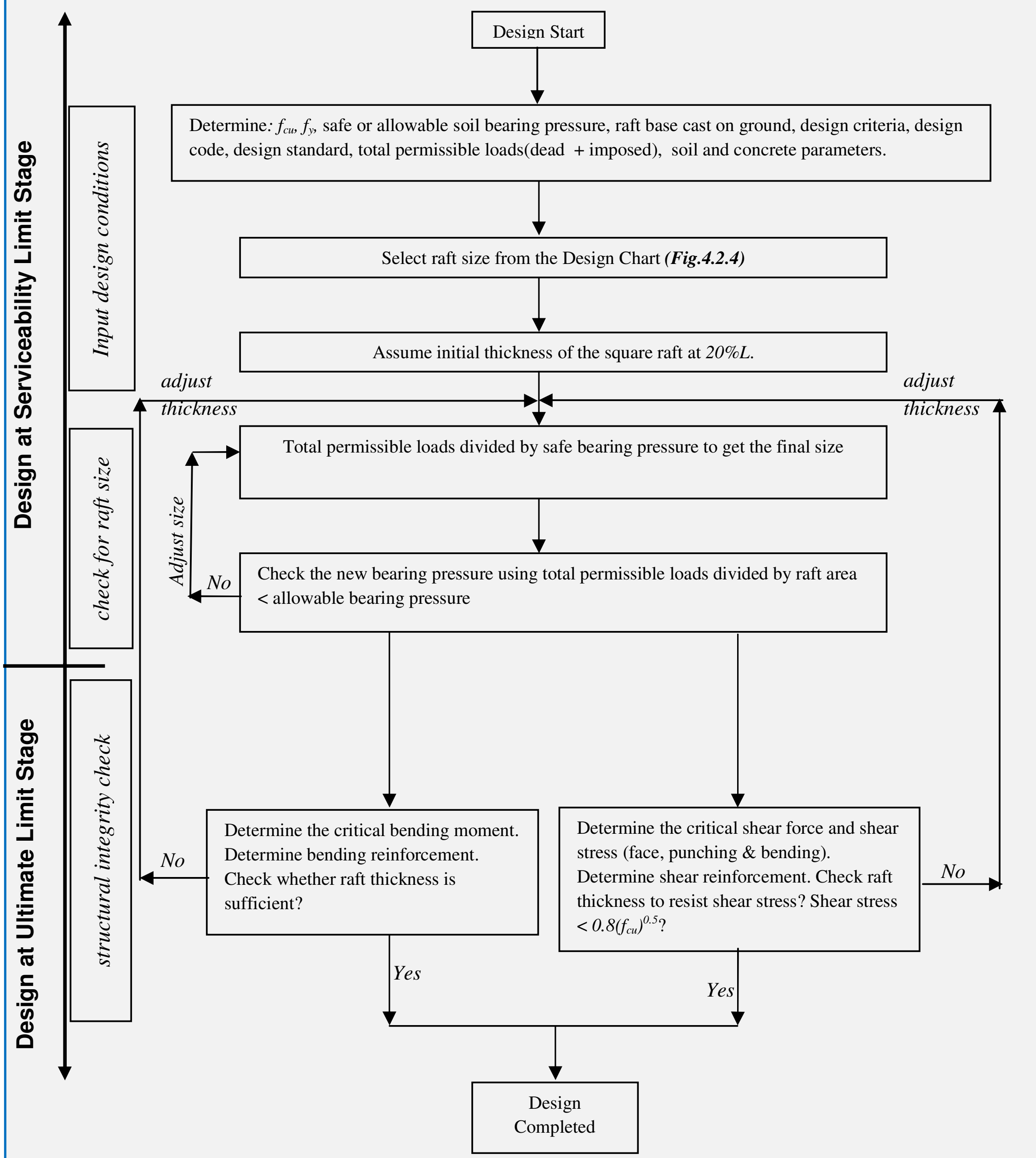

Figure 6.2.1: Flowchart on Raft Foundation

6.3 Step-By-Step Procedures for Raft Foundation Design

Scenario 1: To investigate total permissible load

Step 1. *Check shears strength of the soil immediately below the raft foundation*

Step 2. *Check the size of the raft foundation*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.2.4, Design Table 7.2.1 or Equation 7.2.1.*

Scenario 2: To determine the allowable imposed load

Step 1. *Check shears strength of the soil immediately below the raft foundation*

Step 2. *Check the size of the raft foundation*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.2.4, Design Table 7.2.1 or Equation 7.2.1.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the raft structure.*

Scenario 3: New Design

Step 1. *Check shears strength of the soil immediately below the raft foundation*

Step 2. *Check the size of the raft foundation*

Step 3. *Check the safe soil bearing pressure*

Step 4. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.2.4, Design Table 7.2.1 or Equation 7.2.1. Make sure the total permissible load < safe soil bearing pressure*

Step 5. *Follow Figure 6.2.1 to design the structure of the raft foundation.*

6.4 Worked Examples on Raft Foundation Design

Scenario 1: To investigate total permissible load

Given conditions: -

Cu = 40kPa

Settlement = 25mm

Raft size = 5m x 5m x 0.5m

From Graph (Fig. 4.2.4): -

total permissible load (DL+IL) = 0.093MPa

= 93kN/m^2

Scenario 2: To determine the allowable imposed loads

Given conditions: -

Cu = 40kPa

Settlement = 25mm

Raft size = 5m x 5m x 0.5m

From Graph (Fig. 4.2.4): -

total permissible load (DL+IL) = 93kN/m^2

DL = 12kN/m^2

hence, allowable IL = 81kN/m^2

Scenario 3: New Design

Given conditions: -

Cu = 40kPa

Settlement = 25mm

Raft size = 5m x 5m x 0.5m

Safe bearing pressure = 175kN/m^2

From Graph (Fig. 4.2.4): -

total permissible load (DL+IL) = 93kN/m^2

< 175kN/m^2 ---- O.K

DL = 12kN/m^2 = 300kN

hence, allowable IL = 81kN/m^2 = 2,025kN

proceed to structural integrity check

6.5 Proposed Design Pedagogy for Small Piled-Raft Foundation

Assumption: The square shape piled-raft structure foundation is applied with uniformly distributed loads

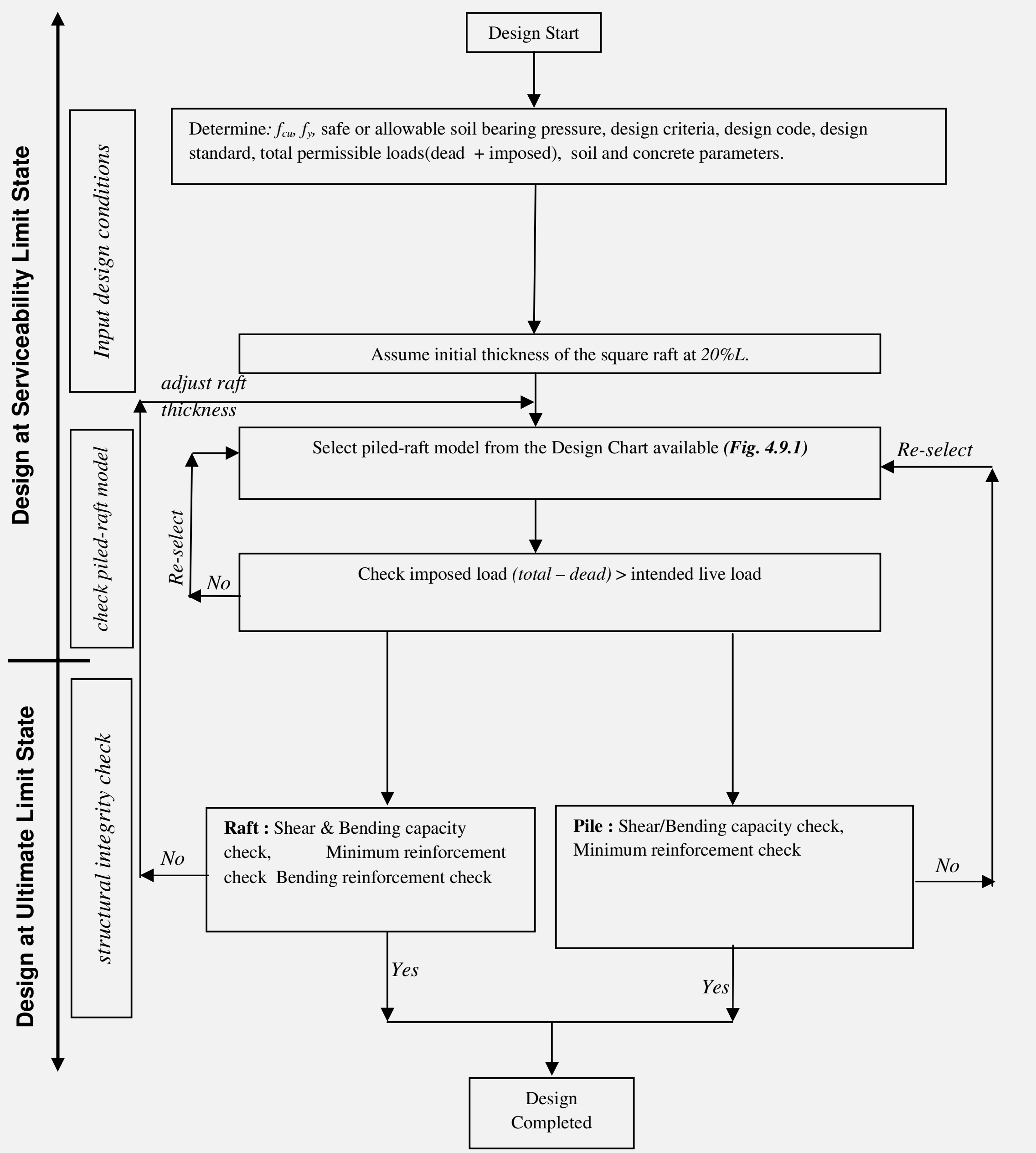

Figure 6.5.1: Flowchart on Small Piled-Raft Foundation

6.6 Step-By-Step Procedures for Small Piled-Raft Foundation Design

<u>Scenario 1: To investigate total permissible load</u>

Step 1. *Check shears strength of the soil immediately below piled-raft foundation*

Step 2. *Check spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.9.1 design chart directly or use the equation given.*

<u>Scenario 2: To determine the allowable imposed load</u>

Step 1. *Check shears strength of the soil immediately below the piled-raft foundation*

Step 2. *Check spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.9.1 design chart directly or use the equation given.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the slab.*

<u>Scenario 3: New Design</u>

Step 1. *Check shears strength of the soil immediately below the piled-raft foundation*

Step 2. *Decide spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.9.1 design chart directly or use the equation given.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the slab.*

Step 5. *Follow Figure 6.5.1 to design the structure of the piled-raft foundation.*

6.7 Worked Examples on Small Piled-Raft Foundation Design

***Scenario 1**: to investigate total load*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Pile = 4 nos at square grid arrangement

From Graph (Fig. 4.9.1): -

total load, TL = DL+IL

Raft size = 5m x 5m x 1m

Table 6.7.1: Total Load

Pile Length	(Raft)	12m	24m	36m
2m pile spacing	24.42kPa	49.98kPa	67.07kPa	83.77kPa
3m pile spacing	24.42kPa	36.16kPa	45.18kPa	54.26kPa

Cum. total loads extracted from Fig.4.9.1 & Fig. 4.9.2

***Scenario 2**: to determine the allowable imposed loads*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Pile = 4 nos at square grid arrangement

From Graph (Fig. 4.9.2): -

total load, TL = DL+IL

Raft size = 5m x 5m x 1m

Table 6.7.2: Allowable Imposed Load

Pile Length	(Raft)	12m	24m	36m
2m pile spacing	IL=TL-DL	IL=TL-DL	IL=TL-DL	IL=TL-DL
3m pile spacing	IL=TL-DL	IL=TL-DL	IL=TL-DL	IL=TL-DL

Total loads extracted from Fig.4.9.1 & Fig. 4.9.2

***Scenario 3**: New Design*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Raft size = 5m x 5m x 1m

4 Piles at square grid arrangement

Pile length = 12m

Pile size = 0.25m x 0.25m

Pile spacing = 2m

From Graph (Fig. 4.9.2): -

total load TL =DL+IL

=24.42kPa + 25.56kPa = 49.98kPa

DL = s/w load,

IL = TL-DL > intended imposed load

Hence, proceed to structural integrity check

Design completed

6.8 Proposed Design Pedagogy for Medium Piled-Raft Foundation

Assumption: The square shape piled-raft structure foundation is applied with uniformly distributed loads.

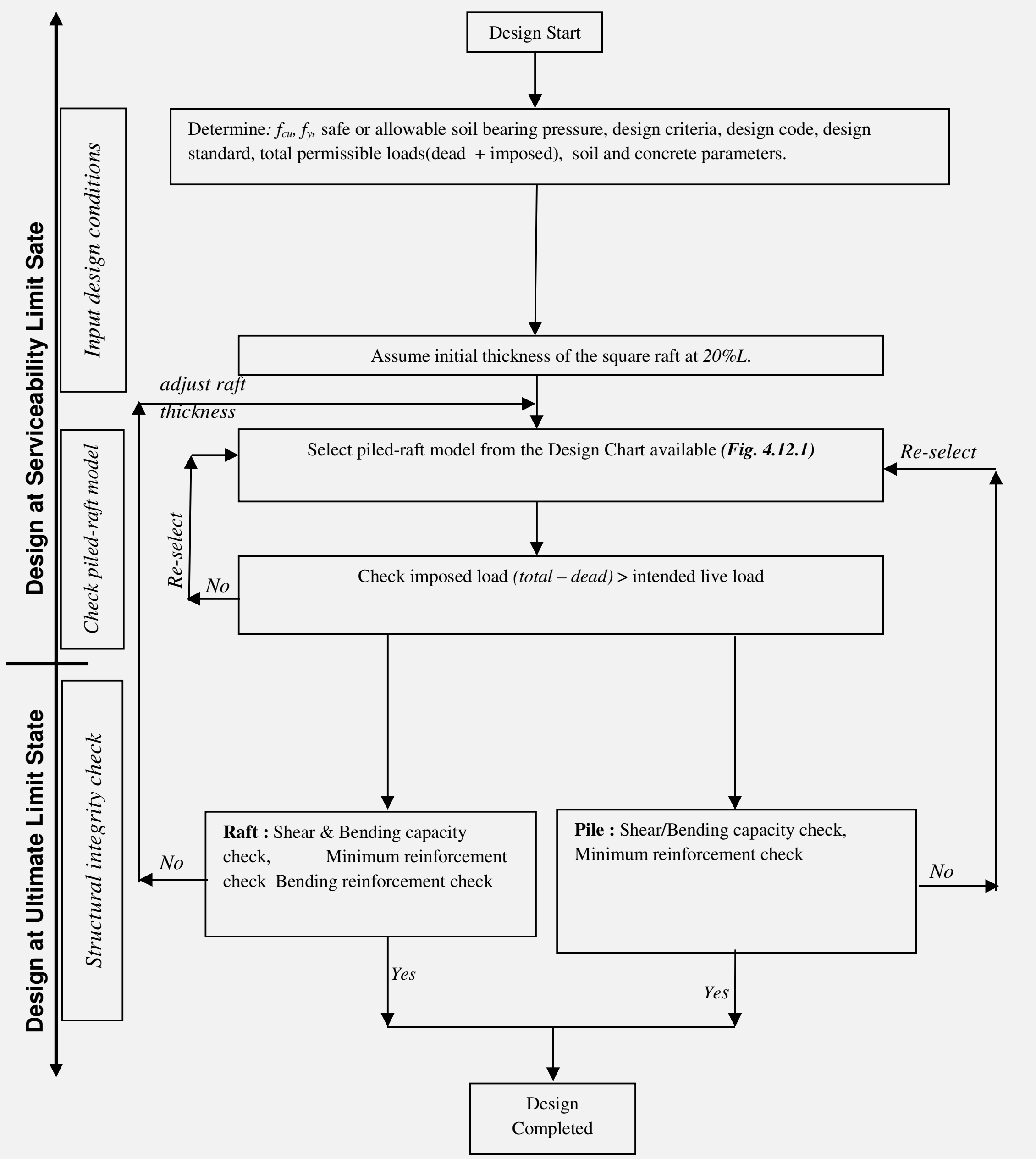

Figure 6.8.1: Flowchart on Medium Size Piled-Raft Foundation

6.9 Step-By-Step Procedures for Medium Piled-Raft Foundation Design

Scenario 1: To investigate total permissible load

Step 1. *Check shears strength of the soil immediately below piled-raft foundation*

Step 2. *Check spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.12.1 design chart directly or use the equation given.*

Scenario 2: To determine the allowable imposed load

Step 1. *Check shears strength of the soil immediately below the piled-raft foundation*

Step 2. *Check spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.12.1 design chart directly or use the equation given.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the slab.*

Scenario 3: New Design

Step 1. *Check shears strength of the soil immediately below the piled-raft foundation*

Step 2. *Decide spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.12.1 design chart directly or use the equation given.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the slab.*

Step 5. *Follow Figure 6.8.1 to design the structure of the piled-raft foundation.*

6.10 Worked Examples on Medium Piled-Raft Foundation Design

***Scenario 1**: to investigate total load*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Pile = 2m spacing at square grid arrangement

From Graph (Fig. 4.12.1): -

total load, TL = DL+IL

Raft size = 10m x 10m x 1m

Table 6.10.1: Total Load (TL)

Pile Length	(Raft) No Pile	12m	24m	36m
2m pile spacing	13kPa	26kPa	50kPa	78kPa

total loads from Fig. 4.12.1

***Scenario 2**: to determine the allowable imposed loads*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Pile = 2m spacing at square grid arrangement

From Graph (Fig. 4.12.1): -

total load, TL = DL+IL

Raft size = 10m x 10m x 1m

Table 6.10.2: Allowable Imposed Load

Pile Length	(Raft)	12m	24m	36m
2m pile spacing	IL_1=TL-DL	IL_2=TL-DL	IL_3=TL-DL	IL_4=TL-DL
Total Allowable Imposed Load	IL_1	IL_{1+2}	IL_{1+2+3}	$IL_{1+2+3+4}$

total loads extracted from Fig. 4.12.1

***Scenario 3**: New Design*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Raft size = 25m x 25m x 2m

100 Piles at square grid arrangement

Pile length = 24m

Pile size = 0.25m x 0.25m

Pile spacing = 2m

From Graph (Fig. 4.12.1): -

total load TL =DL+IL

=50kPa

DL = s/w load,

IL = TL-DL > intended imposed load

Hence, proceed to structural integrity check

Design completed

6.11 Proposed Design Pedagogy for Large Piled-Raft Foundation

Assumption: The square shape piled-raft structure foundation is applied with uniformly distributed loads.

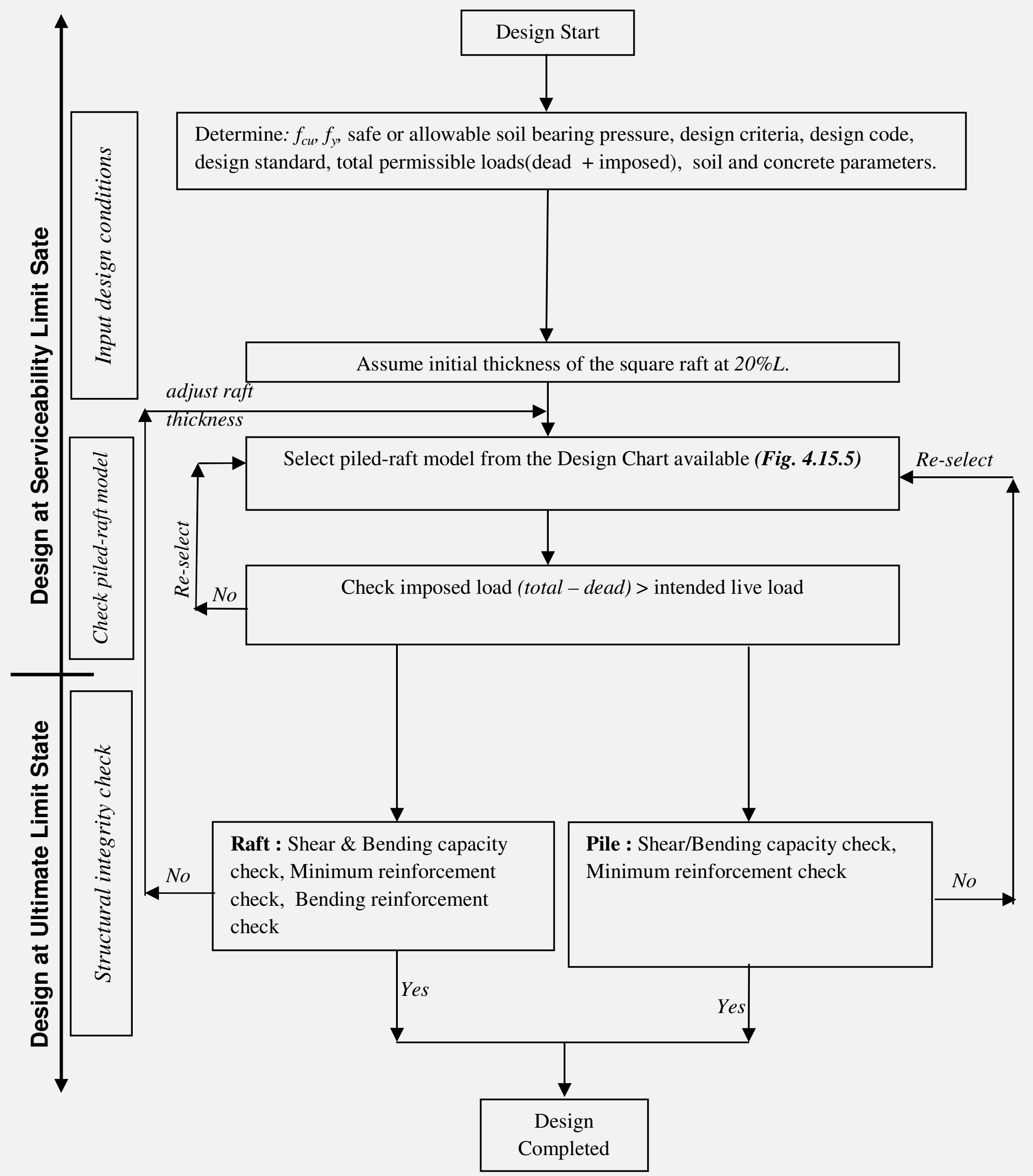

Figure 6.11.1: Flowchart on Large Piled-Raft Foundation

6.12 Step-By-Step Procedures for Large Piled-Raft Foundation Design

Scenario 1: To investigate total permissible load

Step 1. *Check shears strength of the soil immediately below piled-raft foundation*

Step 2. *Check spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.15.5 design chart directly or use the equation given.*

Scenario 2: To determine the allowable imposed load

Step 1. *Check shears strength of the soil immediately below the piled-raft foundation*

Step 2. *Check spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.15.5 design chart directly or use the equation given.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the slab.*

Scenario 3: New Design

Step 1. *Check shears strength of the soil immediately below the piled-raft foundation*

Step 2. *Decide spacing and length of the piles*

Step 3. *Determine the total permissible loads (imposed + self-weight of raft) at 25mm settlement from Figure 4.15.5 design chart directly or use the equation given.*

Step 4. *To find the allowable imposed load, simply use the total permissible loads to offset the self-weight of the slab.*

Step 5. *Follow Figure 6.11.1 to design the structure of the piled-raft foundation.*

6.13 Worked Examples on Large Piled-Raft Foundation Design

***Scenario 1**: to investigate total load*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Pile = 2m spacing at square grid arrangement

From Graph (Fig. 4.15.5): -

total load, TL = DL+IL

Raft size = 20m x 20m x 2m

Table 6.13.1: Total Load (TL)

Pile Length	(Raft) No Pile	12m	24m	36m
2m pile spacing	7kPa	11kPa	29kPa	50kPa

total loads from Fig. 4.15.5

***Scenario 2**: to determine the allowable imposed loads*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Pile = 2m spacing at square grid arrangement

From Graph (Fig. 4.15.5): -

total load, TL = DL+IL

Raft size = 20m x 20m x 2m

Table 6.13.2: Allowable Imposed Load

Pile Length	(Raft)	12m	24m	36m
2m pile spacing	IL_1=TL-DL	IL_2=TL-DL	IL_3=TL-DL	IL_4=TL-DL
Total Allowable Imposed Load	IL_1	IL_{1+2}	IL_{1+2+3}	$IL_{1+2+3+4}$

total loads extracted from Fig. 4.15.5

***Scenario 3**: New Design*

Given conditions: -

Cu = 10kPa

Settlement = 25mm

Raft size = 25m x 25m x 2m

100 Piles at square grid arrangement

Pile length = 24m

Pile size = 0.25m x 0.25m

Pile spacing = 2m

From Graph (Fig. 4.15.5): -

total load TL =DL+IL

=7kPa + 4kPa + 18kPa = 29kPa

DL = s/w load,

IL = TL-DL > intended imposed load

Hence, proceed to structural integrity check

Design completed

CHAPTER 7

CONCLUSIONS

CHAPTER 7: CONCLUSIONS

7.1 Overview

Piled-raft foundation provides an economical option when a raft foundation does not satisfy the design requirement. Under these circumstances, the addition of a limited number of piles would improve the ultimate bearing capacity and the settlement performance. Thus, an extensive parametric studies of piled-raft behaviour has been performed to determine any significant contribution from the raft in the structure-soil interactions i.e. raft-pile-soil interaction.

Over 200 combined load cases models are considered, modelled and analysed through the uses of 3D FEM modelling which is well known as the most accurate numerical methods available. These analyses work are very time consuming; most of the models took an average of 7 hours to complete analysis process while the longest took more than 30 hours to complete.

In all, more than 30 months are spent on these computation works especially during the teething stage.

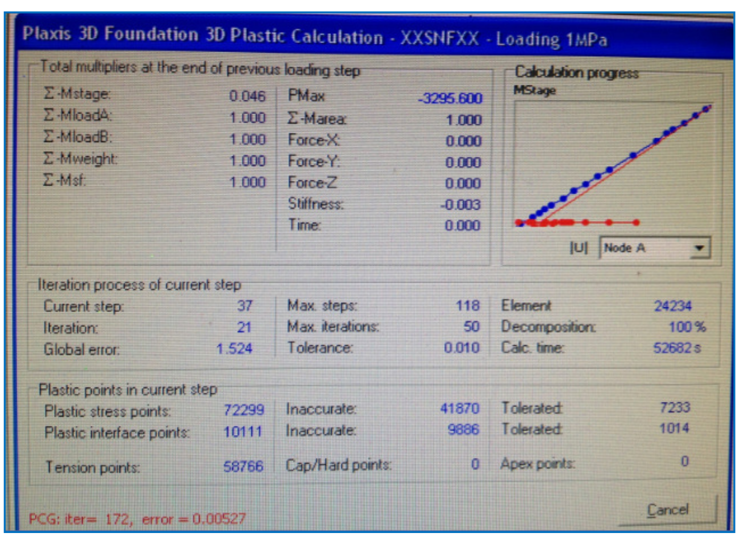

Figure 7.1.1: Screengrab reflecting 3D FEM analyzing time *(52,682s i.e >14hrs)*

Major findings from the research work as follow :-

- The foundation behaved as "flexible" structure under uniformly distributed loads under the sizes considered in this research study;
- Critical settlement point appeared at the center point of raft and its differential settlement is worst in the direction of center to corner of raft;
- Thickness of the raft foundation has little influence on the load bearing against settlement behaviour except having bending stresses generally increase;
- Factor of influence on the foundation load bearing capacity is higher for close-spaced piles foundation followed-by longer pile lengths;
- Under the parametric study in this research work, longer pile length might not necessary be an effective approach because the end-bearing capacity would not be fully utilised especially for foundation settlement during the short-term periods. Another reason is that the load-sharing and moment-sharing are not affected much by increasing of the pile lengths;
- Piles spacing plays an important role on the performance of the piled-raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft and the load shared by the piles;
- The axial load is the maximum at the top of the pile, and it reduces with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases;
- Generally, the contribution of raft is found to be significant on the piled-raft foundation, especially as the pile spacing increased followed by short pile length;
- In general, the rate of settlements for the load-settlement curve seems to increase linearly with the increment of the undrained condition of the soil shear

strength within the elastic limit range probably due to considerable loading at upto 25mm settlements;

- Numerical results used to developed into some design charts are integrated together and converted into a simplified design table (Table 7.2.1);
- Elastic displacement formula was used to evaluate the newly developed design table (Table 7.2.1);
- Published paper and journal are used to benchmark the new design charts and table;
- The results from the general formula (Equation 7.2.1) for foundation design are very much closer to the numerical results compared to the elastic solutions. Hence, this proved that simplified design techniques are reliable and effective;
- Design pedagogies on foundation design that come with self-explanatory design workflows and worked examples are developed.

The research work have been completed with evaluation work done on the design charts and table to permit quick preliminary assessment and design of raft and piled-raft foundation project on planning & cost estimation, or safety and risk analysis studies. In addition, this research work would help the designers and researchers in understanding the significance of the raft in a piled-raft foundation.

This research is identified as being of importance to practical civil and structural engineers in providing design charts and table to perform a quick preliminary assessment and design of foundation, without carrying out complicated and time-consuming 3-D finite element analyses. This is particularly useful when a rapid assessment of the feasibility and construction costs of piled-raft foundation is required during the preliminary design stage.

In summary, the developed simplified design techniques derived from rigorous 3D FEM modelling, which is the most accurate numerical methods as mentioned by *Poulos (2001b),* proved to be more effective than the existing equivalent raft concept's elastic formula due to the soil-raft-pile interactions effect.

Finally, the research work has successfully accomplished with the works been evaluated through overseas peers-reviewed and all technical papers on the research works have also been published in some reputable conferences, congress and international journal.

To summarise, some of these new establishments evolved from this research study presented in Para 7.2 includes :-

i) *New design chart to determine the bearing capacity of raft and piled-raft foundation design which took into consideration of the raft's contribution (Fig. 4.2.4, Fig. 4.9.1, Fig. 4.12.1 & Fig. 4.15.5);*

ii) *New design table on Total Permissible Load developed through the rigorous computation analyse works (Table 7.2.1);*

iii) Proposed Design Pedagogies on raft and piled-raft foundation with work examples and systematic procedures (Para 7.2 Part III).

7.2 Summary

I. General formula used to suit the research work

The general formula used to suit the research study has been modified from the existing *Christian and Carrier (1978)* proposal on the average immediate vertical displacement under a flexible area carrying a uniform pressure. Contribution of the raft from the piled-raft foundation is considered and included in the existing equivalent raft method (Para 5.6).

This general formula (Equation 7.2.1) for calculating the piled-raft foundation bearing capacity that took into consideration the contribution of the raft has proved to be more effective than the former equivalent raft concept's elastic formula when comparing with the numerical study done due to the soil-raft-pile interactions effect in the rigorous 3D FEM modelling. Results difference between 3D FEM Plaxis and the general formula is about 20%. These findings concurred with *Poulos (2001), Lin, D.G. and Feng, Z.Y. (2006)* suggesting loads carried by the pile group could be reduced by almost 25% of the design load depending on the soil condition.

The general formula to determine the total permissible load of a piled-raft foundation, q, is presented below :

$$Si = (qB/E)\mu_0\mu_1 * (B_e/B) \text{ ------------------- Equation 7.2.1}$$

Where:-

- q is the total permissible load of piled-raft
- E is the Young's Modules of undrained soil
- B_e is the distance between 2 outermost piles (refer to Fig. 7.2.1)
- B is the breadth of the equivalent raft (refer to Fig. 7.2.1)
- μ_0 depends on the depth on the earth of embedment and μ_1 depends on the layer thickness and the shape of the loaded area.
- Values of the coefficients μ_0 and μ_1 for Poisson's ratio equal to 0.5 are given in Figure. 5.2.1

Note : this general formula takes into consideration on the contribution of the raft.

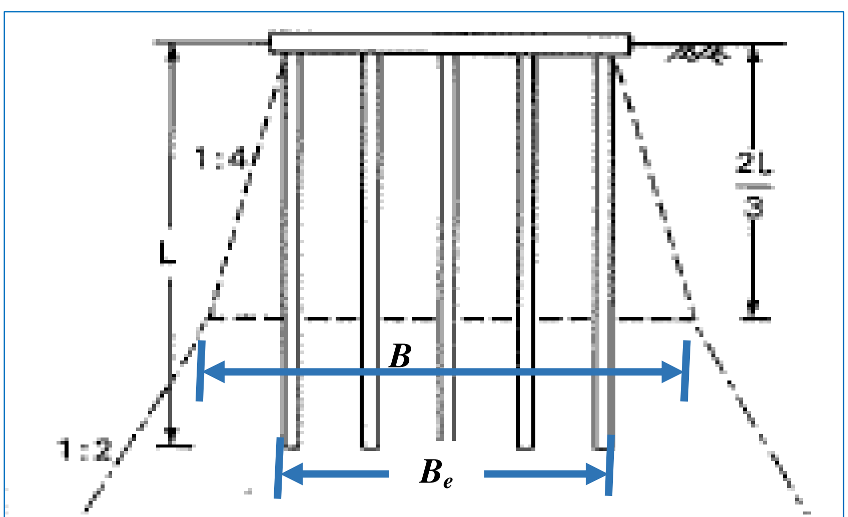

Figure 7.2.1: Modified Equivalent Raft Concept

II. Proposed New Design Chart On Total Permissible Load At 25mm Settlement

The research works on raft foundations ranged from 5m x 5m, 10m x 10m and 20m x 20m are conducted with series of combined load cases considered. The computation results are studied and the bearing capacity information for the raft is presented in a design chart (Fig. 4.2.4).

The research works on piled-raft foundations with sizes similar to the raft foundation models are conducted. All computation results are studied and their bearing capacity information on the piled-raft foundations are individually presented in the three design charts (Fig. 4.9.1 for the small piled-raft model, Fig. 4.12.1 for the medium size piled-raft model and Fig. 4.15.5 for the large piled-raft model).

To establish a versatile design table on load bearing capacities for both raft and piled raft foundation designs, all the four figures (Fig. 4.2.4, Fig 4.9.1, Fig. 4.12.1 & Fig. 4.15.5) are further studied and presented in a versatile Design Table 7.2.1.

This design table 7.2.1 presents the total permissible load for the both the raft and piled-raft foundations. Interpolation works are permissible so long they are within the limits e.g. raft foundation to be from 5m x 5m to 20m x 20m, and piled-raft foundation from 5m x 5m to 20m x 20m with maximum pile length up to 36m deep.

Size of foundation structure	***Total permissible load, q (kPa)***			
	Raft	***Raft with 12m piled***	***Raft with 24m piled***	***Raft with 36m piled***
5m x 5m	$0.0023x + 0.001$	$-0.005x^2 + 4.79x + 2.5$	$-0.0116x^2 + 6.7573x + 0.665$	$-0.0225x^2 + 8.8342x - 2.67$
10m x 10m	$0.00122x + 0.0006$	$-0.0046x^2 + 2.5065x + 1.4858$	$-0.005x^2 + 3.81x + 7$	$-0.024x^2 + 5.1925x + 28.004$
20m x 20m	$0.00064x + 0.0005$	$-0.0025x^2 + 1.095x + 0.25$	$1.1x + 18$	$-0.0075x^2 + 1.885x + 31.75$

NOTE
NOTE 1 : x = shear strength of undrained soil (C_u) from 10kPa to 100kPa
NOTE 2 : The spacing between centre of piles is 2m
NOTE 3 : The values in the table are for immediate settlement of 25mm
NOTE 4 : Extrapolation work permitted on Immediate settlement of up to 40mm
NOTE 5 : Interpolation work permitted with the foundation dimensions

Table 7.2.1: Design Table on Total Permissible Load

III. Proposed Design Pedagogies on Raft and Piled-Raft Foundations With Work Examples

a) For raft foundation design:-

i) refer to Figure 4.2.4 *OR* interpolate from Table 7.2.1 for the load-settlement curve;

ii) refer to Figure 6.2.1 for the proposed design pedagogy;

iii) refer to Paragraph 6.3 for step-by-step procedures;

iv) refer to Paragraph 6.4 for work examples.

b) For 5mx5m plied-raft foundation design:-

i) refer to Figure 4.9.1 *OR* interpolate from Table 7.2.1 for the load-settlement curve;

ii) refer to Figure 6.5.1 for the proposed design pedagogy;

iii) refer to Paragraph 6.6 for step-by-step procedures;

iv) refer to Paragraph 6.7 for work examples.

c) For 10mx10m plied-raft foundation design:-

i) refer to Figure 4.12.1 *OR* interpolate from Table 7.2.1 for the load-settlement curve;

ii) refer to Figure 6.8.1 for the proposed design pedagogy;

iii) refer to Paragraph 6.9 for step-by-step procedures;

iv) refer to Paragraph 6.10 for work examples.

d) For 20mx20m plied-raft foundation design:-

i) refer to Figure 4.15.5 *OR* interpolate from Table 7.2.1 for the load-settlement curve;

ii) refer to Figure 6.11.1 for the proposed design pedagogy;

iii) refer to Paragraph 6.12 for step-by-step procedures;

iv) refer to Paragraph 6.13 for work examples.

7.3 Potential Future Research Areas

This last paragraph wrapped up with some proposal on future research works to improve on this research project study to further explores the significance of raft contribution in piled-raft foundations as the current work only involved the load bearing and settlement behaviours squared foundations under undrained soil conditions.

Some of these potential future research areas include studies on :

- Conduct physical tests on the developed simplified design techniques;
- Drained soil condition;
- Similarity on circular raft and piled-raft foundation;
- Different pile-length formation at strategic locations.

APPENDICES

LISTS OF LOADCASES

Lists of Loadcases for Raft Foundation

Undrained Condition																
Case	Soil parameters (top layer till depth 40m)						Soil parameters (bottom layer @ 40m – 60m)						Raft parameters (Density = 0kN/m^3)			
	c_u (kN/m^2)	E (kN/m^2)	γ_{sat} , γ_{unsat} (kN/m^3)	ν	R_{inter}	K_o	c_u (kN/m^2)	E (kN/m^2)	γ_{sat} , γ_{unsat} (kN/m^3)	ν	R_{inter}	K_o	L × B (m × m)	t (m)	E (kN/m^2)	ν
1u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	5x5	5% of L	2.60E+07	0.2
2u	20															
3u	30															
4u	40															
5u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	5x5	10% of L	2.60E+07	0.2
6u	20															
7u	30															
8u	40															
9u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	5x5	15% of L	2.60E+07	0.2
10u	20															
11u	30															
12u	40															
13u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	10x10	5% of L	2.60E+07	0.2
14u	20															
15u	30															
16u	40															
17u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	10x10	10% of L	2.60E+07	0.2
18u	20															
19u	30															
20u	40															
21u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	10x10	15% of L	2.60E+07	0.2
22u	20															
23u	30															
24u	40															
25u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	20x20	5% of L	2.60E+07	0.2
26u	20															
27u	30															
28u	40															
29u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	20x20	10% of L	2.60E+07	0.2
30u	20															
31u	30															
32u	40															
33u	10	300C_u	16	0.35	1	1	140	300C_u	20	0.3	1	1	20x20	15% of L	2.60E+07	0.2
34u	20															
35u	30															
36u	40															

f Loadcases for Small Size Piled-Raft Foundation – 5m x 5m

UnDrained Condition																			
	Soil parametrics (top layer till depth 40m)					Soil parametrics (bottom layer @ 40m – 60m)					5m x 5m Raft parametrics (Density = 0kN/m³)				Pile parametrics (Density = 0kN/m³)				
²)	E (kN/m²)	γ_{sat} γ_{unsat}	ν	R_{inter}	C_u (kN/m²)	E (kN/m²)	γ_{sat} γ_{unsat}	ν	R_{inter}	L x B (m)	H (m)	E (kN/m²)	ν	Size (m)	Length (m)	n x n	Sp (m)	E (kN/m²)	
															12				
	300C_u	16	0.35	0.67	300C_u	42000	20	0.3	0.67	5 x 5	1	2.60E+07	0.2	0.25x0.25	24	2x2	2	3.00E+07	
															36				
															12				
	300C_u	16	0.35	0.67	300C_u	42000	20	0.3	0.67	5 x 5	1	2.60E+07	0.2	0.25x0.25	24	2x2	3	3.00E+07	
															36				

Appendix C

Lists of Loadcases for Medium Size Piled-Raft Foundation – 10m x 10m

<table>
<tr><th colspan="12">UnDrained Condition</th></tr>
<tr><th rowspan="2">Case</th><th colspan="5">Soil parametrics
(top layer till depth 40m)</th><th colspan="6">Pile parametrics
(Density = 0kN/m^3)</th></tr>
<tr><th>C_u (kN/m^2)</th><th>E (kN/m^2)</th><th>γ_{sat} ,γ_{unsat} (kN/m^2)</th><th>V</th><th>R_{inter}</th><th>Size (m)</th><th>Length (m)</th><th>n x n</th><th>Sp (m)</th><th>E (kN/m^2)</th><th>V</th><th>R_{inter}</th></tr>
<tr><td>1u</td><td>10</td><td rowspan="12">300C_u</td><td rowspan="12">16</td><td rowspan="12">0.35</td><td rowspan="12">0.67</td><td rowspan="12">0.25x0.25</td><td rowspan="4">12</td><td rowspan="12">4x4</td><td rowspan="12">2</td><td rowspan="12">3.00E+07</td><td rowspan="12">0.2</td><td rowspan="12">0.67</td></tr>
<tr><td>2u</td><td>20</td></tr>
<tr><td>3u</td><td>30</td></tr>
<tr><td>4u</td><td>40</td></tr>
<tr><td>5u</td><td>10</td><td rowspan="4">24</td></tr>
<tr><td>6u</td><td>20</td></tr>
<tr><td>7u</td><td>30</td></tr>
<tr><td>8u</td><td>40</td></tr>
<tr><td>9u</td><td>10</td><td rowspan="4">36</td></tr>
<tr><td>10u</td><td>20</td></tr>
<tr><td>11u</td><td>30</td></tr>
<tr><td>12u</td><td>40</td></tr>
<tr><td>13u</td><td>10</td><td rowspan="12">300C_u</td><td rowspan="12">16</td><td rowspan="12">0.35</td><td rowspan="12">0.67</td><td rowspan="12">0.25x0.25</td><td rowspan="4">12</td><td rowspan="12">4x4</td><td rowspan="12">3</td><td rowspan="12">3.00E+07</td><td rowspan="12">0.2</td><td rowspan="12">0.67</td></tr>
<tr><td>14u</td><td>20</td></tr>
<tr><td>15u</td><td>30</td></tr>
<tr><td>16u</td><td>40</td></tr>
<tr><td>17u</td><td>10</td><td rowspan="4">24</td></tr>
<tr><td>18u</td><td>20</td></tr>
<tr><td>19u</td><td>30</td></tr>
<tr><td>20u</td><td>40</td></tr>
<tr><td>21u</td><td>10</td><td rowspan="4">36</td></tr>
<tr><td>22u</td><td>20</td></tr>
<tr><td>23u</td><td>30</td></tr>
<tr><td>24u</td><td>40</td></tr>
</table>

Appendix D

Lists of Loadcases for Large Piled-Raft Foundation – 20m x 20m

UnDrained Condition												
Case	Soil parametrics (top layer till depth 40m)					Pile parametrics (Density = 0kN/m^3)						
	C_u (kN/m^2)	E (kN/m^2)	γ_{sat}, γ_{unsat} (kN/m^2)	V	R_{inter}	Size (m)	Length (m)	n x n	Sp (m)	E (kN/m^2)	V	R_{inter}
1u	10	300C_u	16	0.35	0.67	0.25x0.25	12	2x2	2	3.00E+07	0.2	0.67
2u	20											
3u	30											
4u	40											
5u	10						24					
6u	20											
7u	30											
8u	40											
9u	10						36					
10u	20											
11u	30											
12u	40											
13u	10	300C_u	16	0.35	0.67	0.25x0.25	12	4x4	2	3.00E+07	0.2	0.67
14u	20											
15u	30											
16u	40											
17u	10						24					
18u	20											
19u	30											
20u	40											
21u	10						36					
22u	20											
23u	30											
24u	40											

Continue…………

UnDrained Condition												
Case	Soil parametrics *(top layer till depth 40m)*					Pile parametrics *(Density = 0kN/m^3)*						
	C_u (kN/m^2)	E (kN/m^2)	γ_{sat} ,γ_{unsat} (kN/m^2)	*V*	R_{inter}	*Size (m)*	*Length (m)*	*n x n*	*Sp (m)*	E (kN/m^2)	*V*	R_{inter}
25u	*10*	*300C$_u$*	*16*	*0.35*	*0.67*	*0.25x0.25*	*12*	*6x6*	*2*	*3.00E+07*	*0.2*	*0.67*
26u	*20*											
27u	*30*											
28u	*40*											
29u	*10*						*24*					
30u	*20*											
31u	*30*											
32u	*40*											
33u	*10*						*36*					
34u	*20*											
35u	*30*											
36u	*40*											
37u	*10*	*300C$_u$*	*16*	*0.35*	*0.67*	*0.25x0.25*	*12*	*8x8*	*2*	*3.00E+07*	*0.2*	*0.67*
38u	*20*											
39u	*30*											
40u	*40*											
41u	*10*						*24*					
42u	*20*											
43u	*30*											
44u	*40*											
45u	*10*						*36*					
46u	*20*											
47u	*30*											
48u	*40*											

Continue………..

UnDrained Condition												
Case	**Soil parametrics** ***(top layer till depth 40m)***					**Pile parametrics** ***(Density = 0kN/m^3)***						
	C_u (kN/m^2)	**E (kN/m^2)**	***γ_{sat} ,γ_{unsat} (kN/m^2)***	***V***	***R_{inter}***	***Size (m)***	***Length (m)***	***n x n***	***Sp (m)***	**E (kN/m^2)**	***V***	***R_{inter}***
49u	*10*	*300C_u*	*16*	*0.35*	*0.67*	*0.25x0.25*	*12*	*10x10*	*2*	*3.00E+07*	*0.2*	*0.67*
50u	*20*											
51u	*30*											
52u	*40*											
53u	*10*						*24*					
54u	*20*											
55u	*30*											
56u	*40*											
57u	*10*						*36*					
58u	*20*											
59u	*30*											
60u	*40*											
61u	*10*	*300C_u*	*16*	*0.35*	*0.67*	*0.25x0.25*	*12*	*2x2*	*3*	*3.00E+07*	*0.2*	*0.67*
62u	*20*											
63u	*30*											
64u	*40*											
65u	*10*						*24*					
66u	*20*											
67u	*30*											
68u	*40*											
69u	*10*						*36*					
70u	*20*											
71u	*30*											
72u	*40*											

Continue………….

UnDrained Condition												
Case	Soil parametrics *(top layer till depth 40m)*					Pile parametrics *(Density = 0kN/m^3)*						
	C_u (kN/m^2)	E (kN/m^2)	γ_{sat} ,γ_{unsat} (kN/m^2)	*V*	R_{inter}	*Size (m)*	*Length (m)*	*n x n*	*Sp (m)*	E (kN/m^2)	*V*	R_{inter}
73u	10	300C_u	16	0.35	0.67	0.25x0.25	12	4x4	3	3.00E+07	0.2	0.67
74u	20											
75u	30											
76u	40											
77u	10						24					
78u	20											
79u	30											
80u	40											
81u	10						36					
82u	20											
83u	30											
84u	40											
85u	10	300C_u	16	0.35	0.67	0.25x0.25	12	6x6	3	3.00E+07	0.2	0.67
86u	20											
87u	30											
88u	40											
89u	10						24					
90u	20											
91u	30											
92u	40											
93u	10						36					
94u	20											
95u	30											
96u	40											

APPURTENANCE

LETTERS OF ACCEPTANCE FOR THE

PUBLISHED TECHNICAL PAPERS & JOURNAL

(with peer-reviewed)

The 2nd International Conference on Rehabilitation and Maintenance (ICRMCE)
Innovative Rehabilitation and Maintenance for Sustainable Construction
Solo, Indonesia, 8 – 10 March 2012

in cooperation with

website: http//sipil.uns.ac.id/icrmce02
e-mail: icrmce02@sipil.uns.ac.id and icrmce02@gmail.com

Solo, 29 November 2011

Re: *Referee's Report of the 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering (ICRMCE)*

Dear Er. Tan Kim Leong
Building and Construction Authority, Singapore

Thank you for submitting of your full paper for review and presentation at the 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering (ICRMCE).

The following is the referee's report for your paper.

Paper title:
Sustainable Design for Unpiled-Raft Foundation Structure

Paper ID: B28-096

A. Style and Organization:

1. *Is the paper clearly presented and well organized? Yes, however the author must use the conference paper format or conference paper template*
2. *Is the English satisfactory? yes,*
3. *Is the title appropriate? yes*
4. *Are the figures, tables, and their captions clear? Yes*
5. *Are the references to related work adequate? yes*

B. Scientific Quality (Please check appropriate box):

- X *Contains significant contributions to the advancement of the subject.*
- ❑ *Sound, original, and of interest.*
- ❑ *Does not add to knowledge of the subject.*
- ❑ *Contains fundamental errors.*

C. Recommendation (Please check appropriate box):

- ❑ *Accept as it is.*
- X *Accept with minor revision noted in evaluation statement.*
- ❑ *Accept with major revision.*

- ❑ *Reject.*

D. *Comments: Please summarize the reasons for your recommendation in a statement below or on the reverse side of this sheet.*

1. *The author must use the conference template.*
2. *Please remove the author's CV and put the acknowledgment after paper conclusion (see the conference paper template)*
3. *Put pictures in body text (see the conference paper template)*
4. *Equations must be numbered (see the conference paper template)*

According to the referee, your paper has been accepted for presentation and proceeding of the 2nd ICRMCE. In order to improve your paper in performance in proceeding, you are advised to complete the minor revision referring to the referee's note. The revised paper should be submitted to committee not later than December 10, 2011.

You will have the acceptance and the invitation letter within 14 days.

We look forward to seeing you in the 2nd ICRMCE.

Best regards,

The Committee of the 2nd ICRMCE

The Korean Group of IABSE

18th IABSE Congress

Innovative Infrastructures - Toward Human Urbanism

Seoul, Korea **19-21 September 2012**

Mr. Kim Leong Tan
Building & Construction Authority Academy
200 Braddell Road , Singapore 579700, Singapore

December 14, 2011

Dear Mr. Kim Leong Tan,

On behalf of the Scientific Committee, we are greatly pleased to inform you that your abstract has been accepted at the 18th IABSE Congress Seoul 2012, which will be held on September 19~21, 2012, at Sheraton Grande Walkerhill in Seoul, Korea. We appreciate your interest and contribution to this congress.

Information on Your Abstract:

- **Manuscript ID: Seoul-0464-2012**
- **Title: "Sustainability Design for Piled-Raft Foundation – green initiative"**
- **Presenting Author(s): Tan, Kim Leong**

We send you the Template and Guidelines for the two-page short version and for the full version of your paper.
Please check the attached file.
Please note that the submission of full paper by February 28, 2012.
The reviewers comments (if any) can be found at the bottom of this e-mail.

We congratulate you once again and thank you for your contributions to what promises to be a fruitful congress. If you have any questions, please feel free to contact the Congress Secretariat at secretary@iabse2012.org.

Thank you for your contribution.

Sincerely,

Hyun-Moo Koh, Professor, Ph.D.
Chair, SC for the 18th IABSE Congress Seoul 2012

Delete Reply Forward Spam Move...

18th IABSE Congress-Seoul 2012 - Decision on Manuscript ID Seoul-0464-2012.R2

Friday, June 1, 2012 9:14 AM

From: "secretary@iabse2012.org" <secretary@iabse2012.org>

To: iresontan@yahoo.com

31-May-2012

"Sustainability Design for Piled-Raft Foundation - green initiative"

Dear Mr. Kim Leong Tan:

We are very pleased to inform you that your paper has been ACCEPTED as Oral Presentation for the 18th IABSE Congress Seoul 2012.

Please read the following important instructions for your registration:
1. The presentation author MUST early register for the 18th IABSE Congress and pay the full registration fee by June 30 (Sat), 2012. The papers of those who do not register by the deadline will be automatically withdrawn and discarded from the proceedings.
2. Only the papers of the authors who complete the registration by that date will be included in the 18th IABSE Congress final programme, which will be provided to all participants attending the Congress. For registration information, please visit our official website (www.iabse2012.org).

If you would like to revise your paper, please contact the Congress Secretariat at secretary@iabse2012.org.

We congratulate you once again and thank you for your contribution to what promises to be a fruitful congress.

We very much look forward to seeing you in September in Seoul, Korea.

Sincerely yours,

Hyun-Moo Koh, Professor, Ph.D.
Chair, SC for the IABSE Seoul Congress 2012

Reviewer(s)' Comments to Author:

Reviewer: 1
Comments to the Author
(There are no comments.)

Reviewer: 2
Comments to the Author
(There are no comments.)

TPC(s)' Comments to Author:

INSTITUTE OF RESEARCH ENGINEERS AND DOCTORS

Ref No: - IRED/14/CSEB/ E106
Dated: 3-February-2014

Subject: Letter of Acceptance and Invitation

Dear Author (Tan Kim Leong),

We are pleased to inform you that after hard review process your paper entitled **"Sustainable design technique for foundation structure -green initiative !"** with paper ID **"CSEB-14-205"** has been accepted for Oral presentation and publication in Final Round of "The International Conference On Advances in Civil, Structural, Environmental and Bio-Technology - CSEB 2014" which is going to be held at Kuala Lumpur, Malaysia on 08 - 09 March, 2014. We invite you to present your full research paper in the conference, please bring PPT slides of your paper for presentation in the conference as there are data projectors at the venue.

Benefits of Publication:-

- Your paper will be included in the Conference Proceedings and will be published online with ISBN No and will be archived in SEEK Digital Library so that it will be universally accessed. Seek Digital Library is being accessed by thousands of Students, Researchers and Scientists over the globe. Seek Digital Library is an Open access library. You may visit the Library at www.seekdl.org.
- Each paper will be assigned Digital Object Identifier (DOI) from CROSSREF.
- Registered Papers will be published in various Issues of International Journals with ISSN Numbers.
- You will get the chance to attend the conference and to meet the researchers from the globe.

We have received more than 74 research articles for review in Final Round from more than 14 countries and only 27 articles has been accepted for publication and oral presentation with acceptance ratio of 36.4%. The Review Process has gone through Peer Review Process. The Editorial Committee focused on quality research articles to maintain the credibility of the conference.

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Sustainable Design Techniques for Foundation Structure

- green initiative!

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Abstract—this technical paper serves to provide engineering guidance from the perspective of optimization and valance as the engineering tends to lean on conservatism for practitioners. Thus, the ultimatum is to research and produce some sustainable foundation design techniques for both unpiled-raft and piled-raft foundation structures.

Keywords—load bearing and settlement curves; unpiled-raft; piled-raft; short-term settlement; soil-structure interaction relationships.

1. Introduction

1.1 Background

Piled-rafts structure foundation provides an economical option when an unpiled-raft does not satisfy the design requirement. Under these circumstances, the addition of a limited number of piles will improve the ultimate load capacity and the settlement performance.

In the conventional design approach, piled-raft foundation designs usually ignore any contribution from the raft, and assume that piles carry all the superimposed loads. As a result, the conventional piled-raft designs are often conservative. The overall settlement of piled-raft in such conventional designs is often very small, owing to the installation of longer or more piles than are necessary. Obviously, more economical solutions can be obtained by accounting for the contribution of the raft.

Thus, series of extensive parametric studies of piled-raft behaviour have been performed to determine any significance contribution from the raft in the pile-raft-soil interactions to produce some sustainable design techniques for foundation structure.

1.2 Problem Definition

- Many structures founded on pile-raft structure foundations on soft clay in Singapore have been conservatively designed without considering the contribution from the raft due to the lack of knowledge (and thus design confidence) on the soil-structure interactions, soil load-bearing and settlement behaviours of piled-rafts. This generally resulted in very expensive foundation costs particularly in the soft clay conditions.

- Total settlement is rarely damaging but not differential settlement. However, this can be reduced by prudent design. As highlighted by Terzaghi & Peck, most buildings can tolerate up to 20mm differential settlement. These differential settlements are unlikely to exceed 75% of average total settlements. As such, a maximum settlement of 25mm will be used as a safe guide for buildings on isolated foundation in this paper.

1.3 Objectives

The objectives for this paper:-

- Investigate the undrained bearing and vertical settlement behaviours of raft and piled-raft in the soft clay using 3-D finite element analyses;
- Compute the load bearing contribution by the raft through various simulation from the loaded piled-raft models;
- Develop simplified techniques to permit a rapid preliminary assessment and design of raft and piled-raft for project planning & cost estimation purposes, and safety and risk analysis study; &
- Develop design pedagogy with self-explanatory design flowchart.

2. Geology of Singapore

2.1 General

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Singapore is a small Island covers about 700km^2 that includes the offshore. Climate is hot and humid with an annual rainfall ranging from 1600mm in the southwest to 2500mm in the central regions. Based on these conditions, the rocks are deeply weathered. Hence, various types of sub-soils can be found, and they range from very soft peat and marine clay in the low lying areas to hard rock such as sandstone and granite.

Two main formations; Kallang and Jurong formations have post numerous problems to engineers with regard to the construction of foundations and substructures. This geology, combined with the urbanisation of the island has further highlights the importance of settlement control to all construction projects in Singapore.

2.2 Diagrams Considered

The basic problem addressed is illustrated in *Figure2.2a and Figure2.2b*.

For *Figure 2.2a*, the concrete unpiled-raft foundation is located on the soft clay. Following ranges of matrix parameters were used to establish a sustainable unpiled-raft model:

- raft size, L = *5x5, 10x10, 20x20 m^2*
- raft thickness, t = *5%L, 10%L, 15%L*
- short term maximum vertical settlement, δ = *25mm*

For *Figure 2.2b*, the concrete piled-raft foundation is also site on the soft clay. Following ranges of matrix parameters were used to establish a sustainable piled-raft model:

- raft size, L = *5x5, 10x10, 20x20 m^2*
- raft thickness, t = *5%L, 10%L, 15%L*
- pile = *0.25m x 0.25m*
- pile-length = *12m, 24m, 36m*
- square grid pile-spacing = *2m, 3m*
- short-term vertical settlement, δ = *25mm*

2.3 Finite Element Model

A quarter of the model is used due to symmetry about both axes. Based on the cohesion materials considered, it is preferable to use a simple constitutive model (i.e Mohr Coulomb model). Vertical uniformly distributed load is applied as total load onto the model. Boundaries are placed sufficiently remote so as not to restrict or constrain movements in the area of interest.

2.4 Numerical Analysis

The desktop study and the assessment works done for both unpiled-raft and piled-raft foundation models are used to create some sustainable foundation structure design techniques through the load bearing against settlement computation results retrieve from the 3D-FEM analysis.

All results developed into design techniques (chart& formula) will be validated with theoretical calculation done manually.

3.0 Debriefs on Findings

3.1 Unpiled-Raft Foundation

- Raft model of 5mx5m having highest bearing capacity compared with other larger slabs e.g 10mx10m &20mx20m;
- Thickness of the raft foundation has little influence on the bearing-settlement behaviour except having bending stresses generally increase with it;
- Raft model loaded with uniformly distributed loads has acted and behaved as a flexible structure and displayed a profile of bowl-shape or saddle-shape curve;
- Critical settlement is observed to be at the centre point of the raft and its differential settlement is worst from the centre of the raft to the corner of the raft;
- Elastic displacement formula is used to evaluate the newly developed design chart (Figure 3.3a). It fits well with variation of the results between numerical to theoretical studies of saving of up to 10% due to the rigorous 3D FEM modelling effect;
- When using theoretical method, values of the coefficients μ_0 and μ_1 are very sensitive to the results and interpolation to read from the chart has posed quite a challenge;

3.2 Piled-Raft Foundation

- Thickness of the raft foundation has little influence on the load bearing against settlement behaviour except having bending stresses generally increase;
- The piled-raft raft model loaded with uniformly distributed loads has acted and behaved as a flexible structure and displayed a profile of bowl-shape or saddle-shape curve;
- The critical settlement point is observed to be at the centre point of the raft and its differential settlement is worst in the direction of centre to corner of raft;
- Factors of influence on the bearing capacity is higher for closely spaced piles followed-by lengthen of piles;
- Generally, the contribution of the raft is found to be of significance in the piled-raft foundation, especially as the piles spacing increased followed by short pile length;
- Piles spacing plays an important role on the performance of the piled-raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft and the load shared by the piles;
- Longer pile length might not necessary be an effective approach since the end-bearing capacity would not be fully utilised especially for foundation settlement during the short-term periods. Another reason is that the load-sharing and moment-sharing are not affected much by increasing of the pile lengths;
- The axial load is the maximum at the top of the pile, and it reduces with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases;

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- Elastic displacement formula are used to evaluate the newly developed chart *(Figure 4.2)* and the newly formed formula *(Section 4.1)*;
- The newly formed formula is found to be more effective when compared with the existing elastic displacement formula against the numerical results done due to the soil-pile-raft interactions effect in the rigorous 3D FEM modelling *(Figure 3.3b)*;
- When using theoretical method, values of the coefficients μ_0 and μ_1 are very sensitive to the results and interpolating it from the chart had posed quite a challenge;
- The Elastic displacement formula and the newly formed formula have the same limitation as both did not take into the effect of the spacing of piles and the number of piles;
- A sustainable design chart and a new formula which took into consideration of the raft's contribution in a piled-raft foundation which permit rapid preliminary assessment and design of piled-raft foundation, have been established and evaluated; &
- The differential settlement increases with spacing of piles.

3.3 Evaluation Methods on Developed Design Techniques

- Elastic theory has been found to be useful for evaluation of immediate settlement for cohesive soil condition as highlighted in the book of *U.S Army Corps of Engineers, Settlement Analysis 1994*. Thus, the elastic displacement formula calculation by *Christian and Carrier (1978)* where uniform pressure q is given by: $S_i = (qB/E)\mu_0\mu_1$ for the immediate settlement is used for evaluating these developed design techniques;
- Computation results from the rigorous 3D finite element modelling which allow very rigorous treatment of soil-structure interaction to take place are expected to produce the least conservative load bearing against settlement threshold limit; &
- Lastly the use of the newly formed formula (*Section 4.1* for detail) to calculate the load bearing capacity of the foundation.

In general, above-mentioned three methods relationship can best be presented in *Figure 3.3b*. It can be seen that the newly formed formula has performed better when compared with the existing elastic displacement formula by *Christian and Carrier (1978)*, against the computation results.

4.0 CONCLUSIONS

4.1 Developed New Formula

The newly formed formula is a modification to the existing elastic displacement formula by *Christian and Carrier (1978)*. The new formula takes into consideration of the raft's contribution on the piled-raft foundation by using superposition principle. This newly formed formula is presented as follows :

$$q = S_i EK/(B\,\mu_0\mu_1) \text{ --------} \mathit{TanKL\ (2014)}$$

Where:-

- S_i is depth of the immediate settlement
- E is the undrained soil young's modules at the at top layer
- K is calculated using B/B_e
- ($K = 1$ for unpiled-raft condition)
- B_e is the distance between 2 outermost piles *(Figure 4.1a)*
- B is the breadth of the equivalent raft *(Figure 4.1a)*
- μ_0 depends on the depth on the earth of embedment and μ_1 depends on the layer thickness and the shape of the loaded area.
- Values of the coefficients μ_0 and μ_1 for Poisson's ratio equal to 0.5 are given in *Figure 4.1b*.

4.2 Developed Design Charts

Design Chart *(Figure 4.2)* presents the total permissible load for both the unpiled-raft foundations and piled-raft foundations. Interpolation works are permissible so long they are within the limits e.g raft foundation to be from 5m x 5m to 20m x 20m, and piled-raft foundation from 5m x 5m to 20m x 20m with a maximum pile length of up to 36m deep.

4.3 Design Pedagogy

Design pedagogy is presented in a self-explanation flow chart shown in *Figure 4.3*.

5. Acknowledgement

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Figure 2.2a

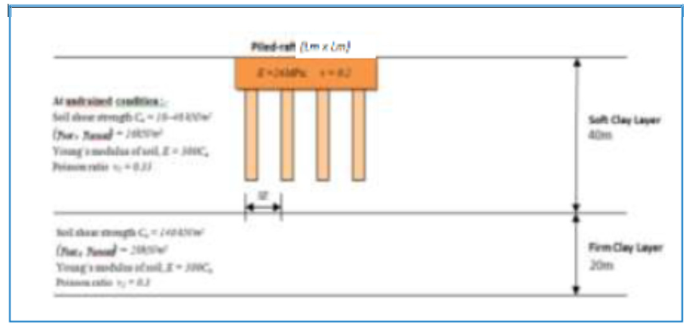

Figure 2.2b

(Sources from Soil Mechanics 5th edition by R.F. Craig)

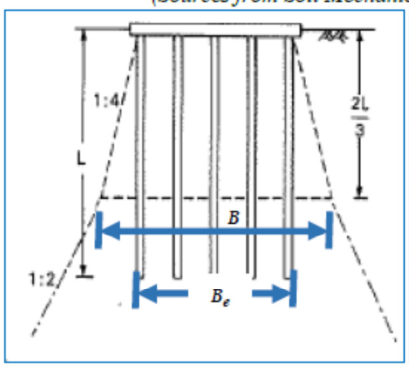

Figure 4.1a

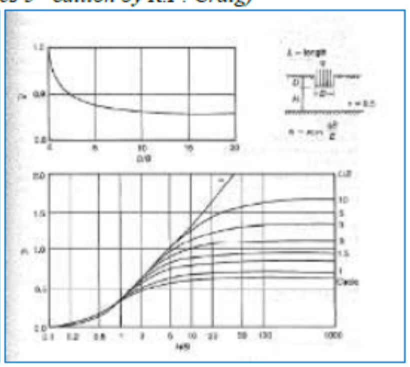

Figure 4.1b

Size of foundation structure	*Total permissible load, q (kPa)*			
	Raft	*Raft with 12m piled*	*Raft with 24m piled*	*Raft with 36m piled*
5m x 5m	$0.023x + 0.001$	$-0.005x^2 + 4.79x + 2.5$	$-0.0116x^2 + 6.7573x + 0.665$	$-0.0225x^2 + 8.8342x - 2.67$
10m x 10m	$0.0122x + 0.0006$	$-0.0046x^2 + 2.5065x + 1.4858$	$-0.005x^2 + 3.81x + 7$	$-0.024x^2 + 5.1925x + 28.004$
20m x 20m	$0.064x + 0.0005$	$-0.0025x^2 + 1.095x + 0.25$	$1.1x + 18$	$-0.0075x^2 + 1.885x + 31.75$

NOTES
NOTE 1 : x = shear strength of undrained soil (C_u) from 10kPa to 100kPa
NOTE 2 : The spacing between centre of piles is 2m
NOTE 3 : The values in the table are for im
NOTE 4 : Interpolation work permitted

Figure 4.2

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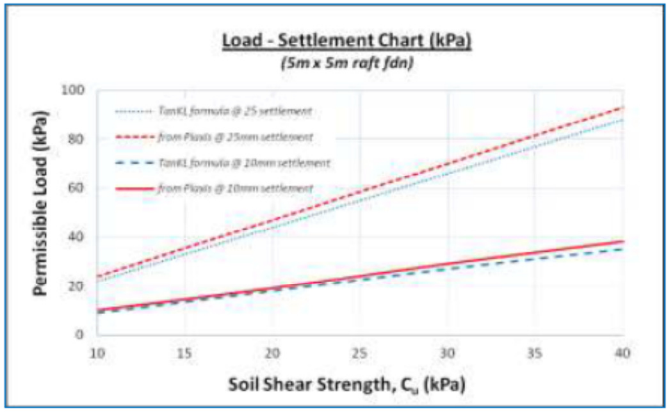

Figure 3.3a

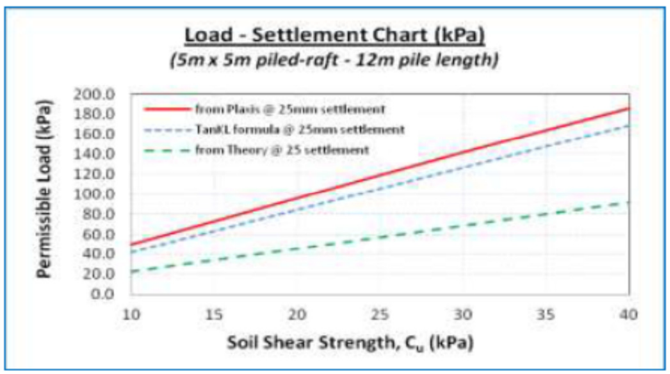

Figure 3.3b

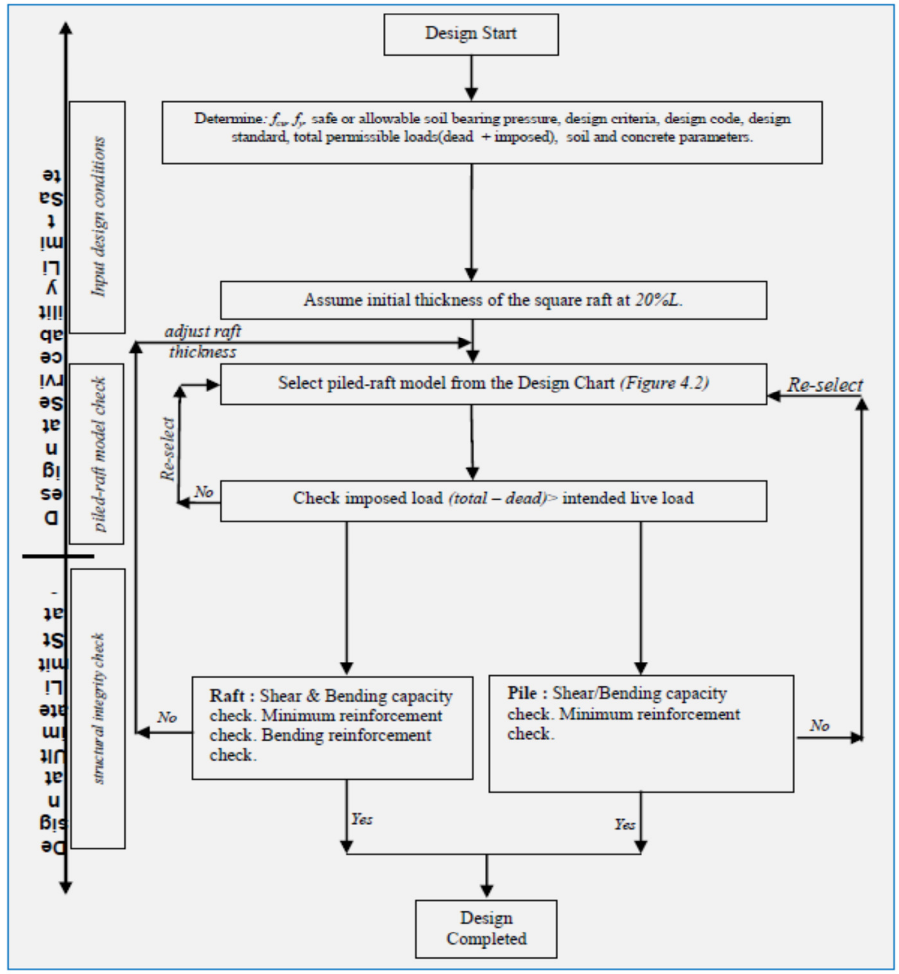

Figure 4.3

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