Compilation of Design Guideline for Piled Raft Foundation

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
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in partial fulfilment of the requirement for the
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Approved by,

(AP Dr Indra Sati Hamonangan Harahap)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JANUARY 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NUR HAYATI BINTI ABDUL RAHMAN

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ABSTARCT

Piled raft foundation is being used widely nowadays, due to its advantages in foundation construction. Piled raft can be used for different cases, such as settlement reducers, and improving bearing capacity of shallow foundation. Piled raft foundation is one of the complex foundation, because it has to consider varies of aspects and consideration. In UTP, especially for civil engineering students, this guideline will help them to learn about piled raft foundation. In this project, one design guidelines will be compiled to help students and others user, in learning the piled raft design. The design guideline will focus on the used of piled raft as settlement reducer for development on soft soil area, where friction pile is used in the design and it will be a "floating" piled raft. In others words, the pile group are not driven until reached the hard layer, but its length will cut at certain depth. Simple calculation methods introduced by various researchers are used in the design calculation, such as Randolph, Poulos and etc. The guideline coverage is ranging from the early staged of soil investigation until design analysis. All the information are collected from the available guideline produced by other parties such as geotechnical consultant, reference books, journals and articles. At the end of this project, one compilation of piled raft design will be documented and together with a spreadsheet, with the objective to assist students in design calculation.

Keywords: Piled raft, settlement reducers, friction pile, negative skin friction, total settlement, differential settlement, load sharing between raft and piles.

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I want acknowledge and thank to G&P Geotechnics Sdn. Bhd for making this project possible. Their contribution range from providing necessary information regarded piled raft design such as articles, journals and also a design guideline for piled raft foundation as my references. To my friends, whose also give some contribution along the project, special thanks to them especially to Mohd Zulhilmi Bin Mokhtar.

Also not to be forgotten, thank you to anyone that have give contribution in this project directly or indirectly.

CHAPTER 1
INTRODUCTION

Piled raft foundation is designed to minimize both total settlement and differential settlement. It also can be used to improve bearing capacity of a shallow foundation and for reducing the internal stress and bending moment within the raft.

The used of piled raft in foundation construction was already implemented a few decades ago in other countries for example Germany. In Germany, piled rafts were first used in the settlement-active Frankfurt Clay, with the intention to reduce the settlement and the risks of building tilting.

In Malaysia perspective, many Malaysian didn't know that Kuala Lumpur City Center (KLCC) is supported by piled raft foundation with different length of piles varying from 60 – 115 meters length. According to original location of KLCC, tower one is located at limestone area and tower two was at Kenny Hill soil area, but after a few construction issues, both tower were moving to Kenny Hill soil area. Due to the greater load from the two towers and the soil condition, settlement and tilting of the structures were become main consideration of the construction. Therefore, piled raft with different length of pile is implemented. See Figure 1.1 for the illustrations of KLCC's foundation.

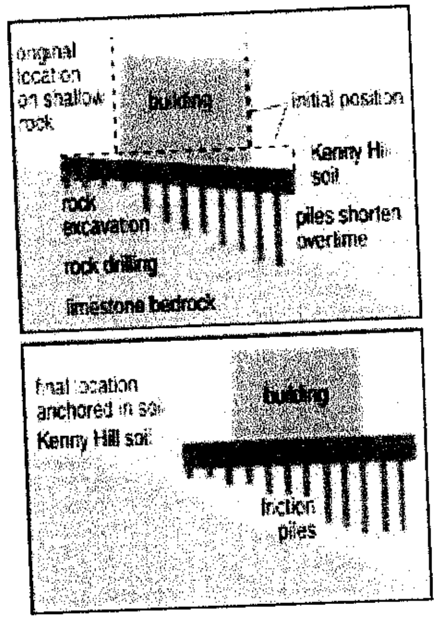


Figure 1.1: Illustrations of KLCC's foundation

The design approach in piled raft foundation is the total load from the structure will be shared between raft and piles, compared with conventional approach using the pile foundation concept, where the entire load will be carried by the piles only. In this approach, the concept of piled raft combines the load-bearing elements of the piles, raft, soil in composite structure and behavior of the piled raft is determined by complex soil-structure interaction effects. The loads from the structure are transferred by the raft via contact pressure with soil, whereas the piles will transfer other portion of the load to the surrounding soil through its shaft friction and also act as settlement controller.

Based on the examples of piled raft foundation given in Germany and KLCC in Malaysia, its give us some information that this foundation can be implemented or used for different types of soil, but for the same purposed. In this thesis, we will only focusing on the implementation of piled raft on soft soil area which is clay deposit. At the end of this thesis, a compilation of design guideline will be attached together and it only can be used in preliminary staged. More discussion on this design guideline will be at Chapter 4.

1.1 Background Study

In Malaysia, piled raft foundations have been implemented in various types of construction. Eventhough, the piled raft it still not widely used, it is giving more advantages compared to pile foundation especially in term of settlement, differential settlement and also the serviceability of the structures.

As explained in the introduction, our main case study will on the design of piled raft on clay deposit for small structures such as houses. Piles will act as settlement reducers because in this case, settlement of the structure and soil will be our main consideration. Friction pile is used to reduce the settlement by using the negative skin friction of the pile. It also used to transfer a portion of the total load to the surrounding soil.

In this concept, the piles would not fully penetrate into the subsoil until it reaches the hard layer or bed rock. It will drive until reach specific depth, and cut into particular length, normally can range between 6 meter to 30 meter and more, depend on the subsoil condition and the settlement. The piles will be allocated beneath the raft and for the part where the load is higher; more piles will be placed to reduce the settlement for that particular part.

1.2 Problem Statement

In the Civil Engineering courses, students are not exposed to the design of piled raft in their study, especially in the foundation engineering course. They may learned about it, but only for theoretical not as practical. Therefore, most of the students don't have knowledge about the design of piled raft foundation.

For a student to learn about the design of piled raft in detailed, software is required in order to carry out or run the analysis of the design. This is because piled raft foundation is one of the complex foundations and need to consider the interactions inside the piled raft, such as pile-raft interaction, pile-soil interaction and etc.

This project will be compiled a design guidelines for piled raft foundation, for students to learn and design piled raft. The analysis of the piled raft can be done by using simple hand calculation. Therefore, student can learn how to design the piled raft without using any software. Spreadsheet will be also provided to assist students in designing the foundation for easy and fast calculation.

1.3: Objectives and Scope of Works

The objectives on this research are as follows:

i. To help and guide UTP student especially to learn and understanding the design of piled raft in easy method.
ii. To compile and documented recent design guidelines for piled raft foundation.
iii. Developed an engineering spreadsheet to assist student in their design calculation.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Piled raft is a geotechnical composite construction consisting of three elements, piles, rafts and soil. Randolph (1994) has defined clearly three different design philosophies with respect to piled rafts foundation:

- Conventional approach, in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft, primarily to ultimate load capacity.

- Creep Piling, in which the piles are designed to operate at a working load at which significant creep start to occurs, typically 70-80% of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the pre-consolidation pressure of the soil.

- Differential settlement control. In which the piles are located strategically in order to reduce the differential settlements, rather than to substantially reduce the overall average settlement.

De Santis et al (2001) and Viggiani (2001) have distinguished between two (2) classes of piled raft foundation:

- "Small" piled rafts, those in which the bearing capacity of unpiled raft is insufficient, and thus the primary reason to add piles is to achieve a suitable safety factor. The flexural stiffness of the raft is usually high and the differential settlement does not represent a problem.

- "Large" piled rafts, those in which the bearing of capacity of raft is sufficient to carry load from the structure and the addition of piles is to reduce the settlement.

2.2 Design Issues

As with any foundation system, a design of piled raft foundation required a few of consideration when designing the foundation:

- Bearing capacity of the piled raft
- Piled raft stiffness
- Average settlement
- Differential settlement
- Load-sharing between raft and pile group

2.3 Design Process

A design process for piled-raft foundation basically involves two (2) main stages:

- Preliminary design
  Usually to obtain the overall view of the design, and can be done by using simple hand calculation. The data that obtained are usually estimated values such as average settlement and differential settlement.

- Detailed design
  In the detailed design, sufficient software is required in order to do the analysis. This is because, it need to include all the interaction inside the analysis. Usually, in this staged a few designed spreadsheet will be used to obtain the detailed values such as settlement contour, pile reaction, soil stiffness, and bending moment and shear forces along the strip of the raft.

2.4 Classification of methods of analysis

There are several methods of analyzing the behavior of piled raft, some of these have been summarized by Poulos et al (1997). Three (3) broad classes of analysis method have been identified and have been stated as below, but in the design guideline, we only used simplified hand calculation:

- Simplified calculation methods
  Using a simple formulas, that be calculated manually

- Approximate computer-based methods
  Using a sufficient software, such as SAFE

- More rigorous computer-based methods
  Using a Finite-element based method or software such as PLAXIS

2.5 Piled raft interactions

Piled raft foundation is a complex structure. There are few of interactions that need to consider in the piled raft design. Below are four (4) main interactions that need to be analyzed:

- Pile – raft interaction
- Pile-pile interaction
- Pile –soil interaction
- Raft – soil interaction

These interactions can be analyzed if software is used, but for this project, we only used simple hand calculation. Therefore, only a few interactions can be analyzed.

2.6. Formulas used in design guideline

2.6.1 Number of piles required and spacing

Number of piles required can be determined by obtaining allowable load per load and the equation as below:

Allowable load per pile:

Surface area of piles

$= d_p$ x no.of pile surface x L_p (Square pile = no of surface = 4) (2.1)

where;

d_p = diameter of pile

L_p = length of pile

Allowable skin resistance

$$= \frac{q_u}{2} \times \frac{\alpha}{FS} \quad (2.2)$$

where;

q_u = unconfined shear strength

α = reduction coefficient (Refer Figure)

FS = factor of safety

Allowable load per pile = Surface area of piles x Allowable skin resistance (2.3)

Number of piles required = Applied load / allowable load per pile (2.4)

Spacing

Minimum spacing = 3d

2.6.2 Bearing capacity of piled raft

In determining the bearing capacity of piled raft, the following equation can be used:

Based on the Terzaghi bearing capacity equation, bearing capacity of raft can be determined by

$$\text{Net bearing capacity} = c.\,N_c \qquad (2.5)$$

$$= \frac{q_u}{2}.\,N_c$$

where;

q_u = unconfined compressive strength

Nc = Terzaghi bearing factor

= 5.14 (continuos foundation)

For safety bearing pressure (sbp), a factor safety can be added into the equation as below:

$$\text{Sbp} = \frac{\text{net bearing capacity}}{\text{F}} \qquad (2.6)$$

$$= \frac{q_u.N_c}{6}$$

where;

F = factor of safety (F = 3)

To hold good for a footing of any rectangular shape, Eq. (8.2) can be modified by adding 'shape factor' into the equation. The Terzaghi bearing capacity factor N_c, according to Skempton, is influenced by both shape of the footing and its depth. As regards shape he considers the influence of the 'aspect ratio' (B/L), 'shape factor' is used because it is seen to be linear function of 'aspect ratio'.

$$\text{Sbp} = \frac{q_u N_c}{6} \times \underbrace{\left[1 + 0.2\frac{B}{L}\right]}_{\text{shape factor}} \tag{2.7}$$

where;

B = width of raft

L = length of raft

Bearing capacity of raft

= Area of raft x sbp (2.8)

To obtain the bearing capacity of piled raft, we have to determine the pile group of surface shear and the equation used as follows:

Surface area

$= (2B \times L_p) + (2L \times L_p)$ (2.9)

Allowable shear

$= \frac{C}{F}$

$= \frac{q_u}{2.F}$ F = 3

$= \frac{q_u}{6}$ x surface area (2.10)

Piled raft bearing capacity

= Bearing capacity of raft + Allowable shear (2.11)

2.6.3 Raft Stiffness

The average raft stiffness, acting alone can be estimated by using proposed equation by Richart et al., 1970. The equations are as below:

i. Circular raft

$$k_r = 4G_s r_o/(1 - v_s) \quad (2.12)$$

ii. Rigid rectangular raft

$$k_r = [G_s/(1 - v_s)]B_z(4cd)^{\frac{1}{2}} \quad (2.13)$$

where;

G_s = soil shear modulus

v_s = soil poisson's ratio

c = L/2

d = B/2

r_o = the circular raft radius

B_z = a coefficient depending on the raft dimensions, c and d.

Refer to the Figure 2.1 below to obtain B_z coefficient.

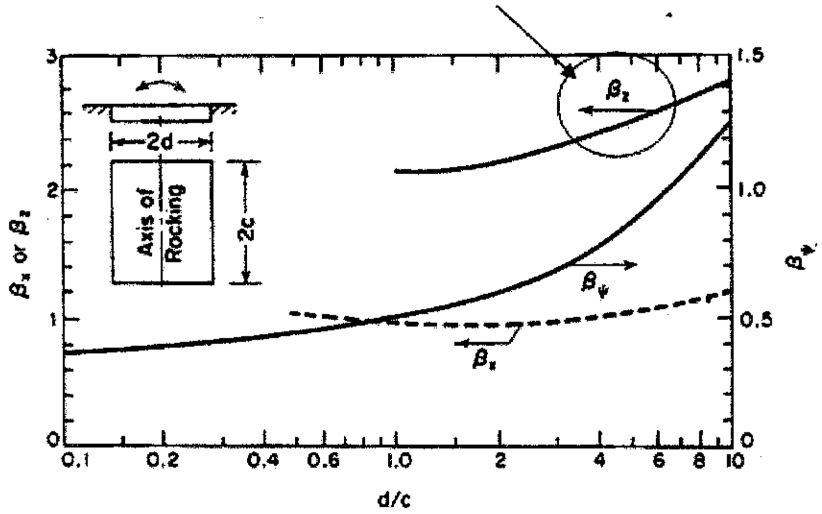


Figure 2.1: Coefficients Bz, Bx, and Bψ for rectangular footings (after Richard et al, 1970)

2.6.4 Pile group stiffness

2.6.4.1 Single Pile Response/Stiffness

For straight-shafted friction pile where $\eta = \xi = 1$, the equation will be as below:

$$\frac{P_t}{G_l r_0 w_t} = \frac{\left[\frac{4}{(1-\nu)}\right] + \left\{\left(\frac{2\pi\rho}{\zeta}\right)\left(\frac{\tanh(\mu l)}{\mu l}\right)\left(\frac{L_p}{r_0}\right)\right\}}{1 + \left\{\left(\frac{4}{\pi\lambda(1-\nu)}\right)\left(\frac{\tanh(\mu l)}{\mu l}\right)\left(\frac{L_p}{r_0}\right)\right\}} \tag{2.14}$$

where;

υ= Poisson's ratio of the soil

ρ= Measure of the vertical homogeneity of the soil stiffness

$\zeta = \ln(r_m/r_o)$ $r_m = 2.5\rho\,(1-\upsilon_s)L_p$

$\mu L = (\sqrt{2/\zeta\lambda})(L_p/r_o)$

L_p = Pile length

r_o= Radius of pile shaft

2.6.4.2 Pile Group Response / Stiffness

Efficiency Approach

Based on the method introduced by Fleming et al. (1992), the pile group efficiency is written as:

$$\eta_w = n^{-e} \tag{2.15}$$

where;

n = number of piles in a group

e = exponent, which is lie between 0.4 and 0.6 for most pile group.

The exponent, e is actually depending on below factors, which are:

- Pile slenderness ratio, L_p/d_p
- Pile stiffness ratio, $I = E_p/G_l$
- Pile spacing ratio, s/d_p
- Homogeinity of soil, characterized by r
- Poisson's ratio, υ

Thus, based on the above formula, pile group stiffness (k_p) can be determined by:

$$k_p = \eta_\omega \eta k_1 \tag{2.16}$$

where;

k_1= stiffness of a single pile from equation 2.1

2.6.5 Differential Settlement

2.6.5.1 Raft

Horikoshi and Randoplh (1997) proposed that the raft- soil stiffness for rectangular rafts with dimension B (width) by L (length), where B ≤ L, are defined as below:

$$k_{rs} = 5.57\left(\frac{E_r}{E_s}\right)\left[\frac{\left(1-\nu_s^2\right)}{\left(1-\nu_r^2\right)}\right]\left(\frac{B}{L}\right)^{0.5}\left(\frac{t_r}{L}\right)^3 \qquad (2.17)$$

Where

E_r = Young's modulus of raft

E_s = Young's modulus of soil

ν_r = Poisson's ratio of raft

ν_s = Poisson's ratio of soil

t_r = thickness of the raft

Thus, the differential settlement of the raft will determine by referring to figure 2.2 below:

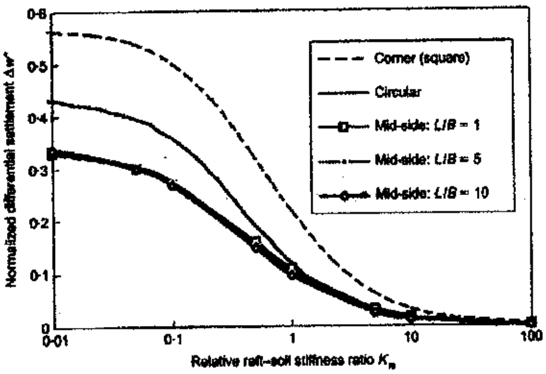


Figure 2.2: Variation of normalised differential settlement with raft-soil stiffness ratio, K_{rs} (after Horikoshi & Randolph, 1997)

2.6.5.2 Pile Groups

To determine the differential settlement of pile, Randolph (1994) has proposed an equation, where this equation is used to estimate the normalized differential settlement for pile group.

$\Delta w / w_{avg} \approx f\,(R / 4)$ for $R \leq 4$ (2.18)

$\Delta w / w_{avg} \approx f$ for $R > 4$. (2.19)

where;

f = 0.3 for centre to mid-side

f = 0.5 for centre to corner

2.6.6 Load Distribution between Raft and Pile Groups

The overall piled raft stiffness and load distribution can be calculated by using a simple piled raft analysis proposed by Randolph.

The piled raft stiffness, k_{pr}

$$k_{pr} = \frac{[k_p + k_r(1-2\alpha_{rp})]}{1-\alpha_{rp}^2\left(\frac{k_r}{k_p}\right)} \tag{2.20}$$

The load distribution carried by raft (P_r) and piles (P_p) is as below:

$$\frac{P_r}{(P_r + P_p)} = \frac{[k_r(1-\alpha_{rp})]}{[k_p + k_r(1-2\alpha_{rp})]} \tag{2.21}$$

where;

α_{rp} can be determined by:

$$\alpha_{rp} = \frac{\ln(r_m / r_r)}{\ln(r_m / r_0)} = 1 - \left(\frac{\ln(r_r / r_0)}{\zeta}\right) \tag{2.22}$$

where;

r_m = radius of influence of the piles

r_o = radius of the pile

r_r = effective radius of the element of raft associated with each pile

CHAPTER 3
METHODOLOGY

In this Final Year Project (FYP), the methodologies that used are basically based on:

3.1 Research

The research phase is already started last semester by referring articles, journals and paper conferences. Most of the information is obtained from the publication website such as Springer Link.

Research also done by referring publication from consultant company and also from books. One design guideline from one of geotechnical consultant company is used as references in the process of compiling the design guideline

3.2 Compiling

The information gathered from the research, will be edited and compiled to create one (1) design guidelines. The information is arranged according to design step, in which it start with early phase of design step, followed by the next phase until it final phase. The guideline is design to be comprehensive, with more explained, so readers will gain more understanding and have some knowledge after finish reading this guideline.

3.3 Development of Spreadsheet

In this project, our main objective is to help student to learn about piled raft design, so in order to achieve that objective, an engineering spreadsheet will be develop to assist student in their design calculation. This spreadsheet is created using Microsoft Excel.

The spreadsheet is actually the easier method to do the design calculation, because the entire step required and formula needed are already created in the spreadsheet. Users only have to key in the main value, and they will obtain the value that they need.

CHAPTER 4

RESULT & DISSCUSSION

4.1 Result

In this project, the final outcomes are the:

i. Compilation of design guideline

This design guideline is a compilation of the information gathered in research phase. Together with the guideline, a sample of design is provided for the students to learn how to design piled raft by using the example given.

The design guideline is comprised of 9 chapters and brief explanation at discussion part. The 9 chapters are as below:

- Introduction
- Procedure for foundation selection
- Design approach and consideration
- Subsurface exploration

- Laboratory tests that commonly done in foundation design
- Soil parameters that required
- Piled raft parameters
- Design calculation
- Design analysis

ii. Spreadsheet for design calculation

A spreadsheet, created using Microsoft Excel is also provided together with the design guideline. The spreadsheet is consists of the calculation steps required in the design. The users only have to key in main value, and the spreadsheet will automatically calculated. What users will get is final value that is required, for example the piled raft bearing capacity. No need to calculate it manually.

The compilation of design guideline and the spreadsheet can be referring to the Appendices at end of this thesis. The formulas used in the design guideline and the spreadsheet are already explained in the literature review.

4.2 Discussion

Current design of piled raft has ignored any contribution from the raft to carry part of the total load from the structure. The piles are designed to carry the total load and from economic perspective, this approach is uneconomical and conservative. The foundation designed in such a way often required more piles than are necessary.

Theoretically, for optimum design, the role of raft had to be taken into consideration. But in construction perspectives, taken load-sharing between raft and piles will cause the construction of foundation becomes crucial. An intensive construction controlling should be done during construction to make sure that the raft has contact pressure with soil. This is because, to make the raft took some load, it must have direct contact with the soil, so the contact pressure can be formed.

As explained in the introduction, raft transmitted the load through contact pressure with soil, but if there no contact with raft and soil, raft can't transfer the load. If there have the gap between the raft and soil due to several factors, for example the error during construction execution or the soil beneath the raft is settled, contact pressure between raft and soil would not happen.

That why, most of the designer neglected the role of raft and assumed the piles taken 100% of the load, due to its crucial construction method. This also to take a safe method, because if the there have the problem with raft's function, it will not affect the structures because the piles are already designed to take 100% of the load. Role of raft can be considered, but it needs crucial construction method and controlling during construction. But, the guideline still focused on the load-sharing in the design calculation for education purposed.

4.2.1 Design Approach

According to Randolph (1994), there are three (3) design approaches in the piled raft design, but based on the formulas used, we only focus on the two (2) approaches, which are:

i. Conventional approach
ii. Differential settlement control

In conventional approach, the piles will be distributed uniformly beneath the raft with regular spacing. The primary aim is to control the settlement to an acceptable amount. The raft will be allowed to transmit some portion of load through contact pressure to the ground. The piles will carry 60%-75% of total load and transferred it into the surrounding area through its surface area. Thus, the number of piles will be reduced due to the role of raft is taking into the calculation.

The foundation is designed to allow the structure to be settled together with its surrounding area, therefore a "floating" piled raft is implemented. What it means by "floating" is the length of the piles will be cut to the specific depth and not until it reaches the hard layer or bed rock. The settlement will be controlled by the friction piles through shaft friction, which act as upward forces.

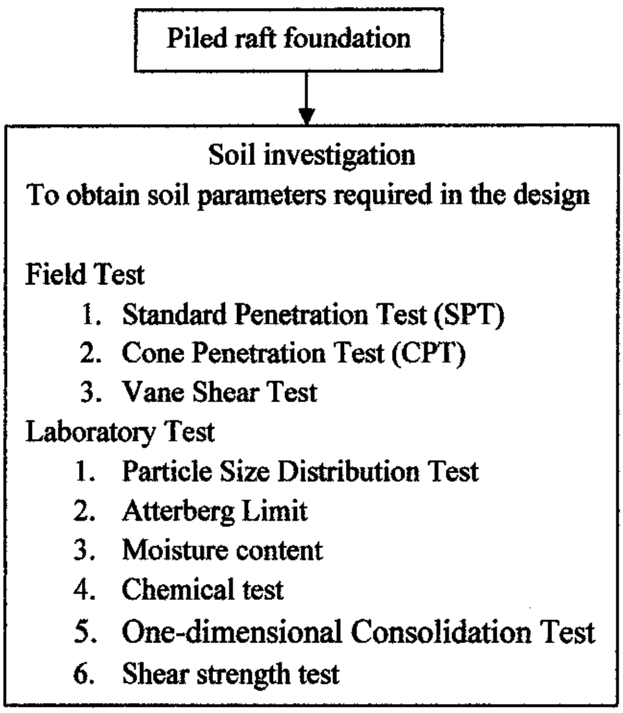
In soft soil area development, the used of pile foundation can course a gap between the structure and the ground. As we know, the pile foundation is designed in such a way to eliminate the total settlement of the structures, where the piles will be installed until it reached the hard layer or bed rock. The foundation only supported the structure but not its surrounding area, which is still settled through times. Therefore, a gap can be formed between the structure and the ground, thus can caused serviceability failure, such as crack. Different situation in "floating" piled raft, where the structure is allowed to settle together with its surrounding area, the tendency to have a gap between the structure and its ground can be said minimum. Thus, there will no serviceability failure of the structure.

For design approach of the raft, there are basically two approaches have been suggested for analyzing the behavior of raft, which are as below:

i. Rigid foundation approach
ii. Flexible foundation approach

Based on these two approaches, both have different advantages and also disadvantages. In rigid approach, the raft will be designed with thicker depth, whereas in flexible approach, the depth of raft will be thinner. The advantages with thicker depth, the differential settlement will be comparatively low but higher in bending moment and shear forces. For thinner raft, the differential settlement will be higher but it will lead to low bending moment and shear forces within the raft. So, the designer can choose either method for the design.

4.2.2 Flow chart of design procedure for pile raft foundation



Structural layout

Column location and load
(dead load + live load)

↓

Preparation of information

- Structural column locations and loading plan
- Raft, pile and soil parameters

↓

Raft's parameters required

1. Young's Modulus, E_r
2. Poisson's ratio, v_r
3. Raft dimensions; width and length (depend on the base area of the structure)
4. Raft thickness

↓

Pile's parameters required

1. Young's Modulus, E_p
2. Pile length, L_p
3. Pile diameter, d
4. Pile spacing, center to center, s
5. Number of piles, n

↓

Soil's parameters required

1. Young's modulus of soil, E_s
2. Poisson's ration, v_s
3. Shear modulus of soil, G_s
4. Undrained shear strength, c_u

↓

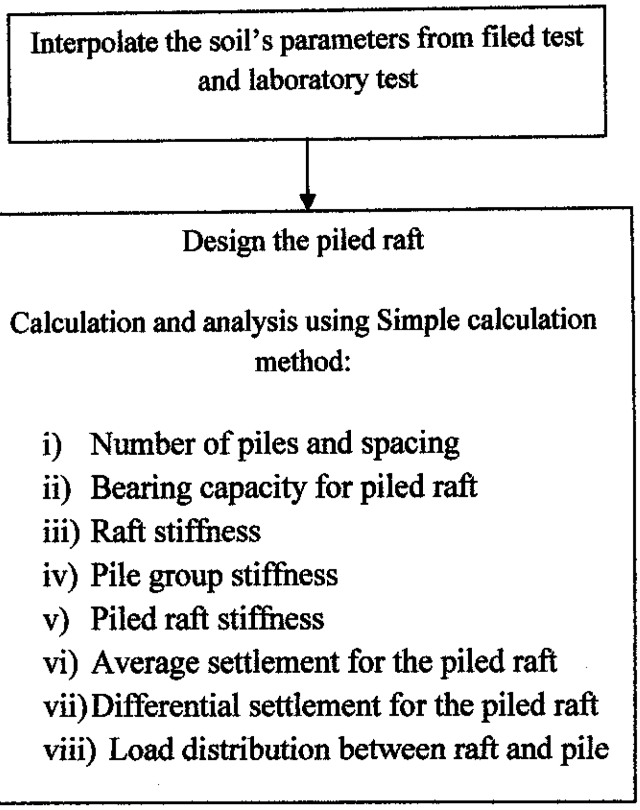


Figure 4.1: Flowchart of design procedure for piled raft

4.2.3 Subsurface Investigation, Field Test and Laboratory Test

Based on the flow chart given above, it shows the steps to design the pile raft, such as what data that needed in the design and also how to get the required data. Basically, subsurface investigation (SI) or subsurface exploration will be carried out.

"Subsurface exploration" is a process of identifying the characteristics of the subsoil at proposed project site, such as type of the subsoil underlies the proposed site. During this stage, a few field tests will be carried out at the project site, which are consists of making test boreholes and collecting sample at specified interval of depth. The depth interval can be changed during the drilling operation, depending on the subsoil encountered. The selection of the boreholes will be decided by the engineer and normally it will depend on the topography of the proposed site. In the foundation design in soft clay, the main consideration is settlement, so a few in-situ tests or field test will be carried in order to obtain the soil settlement parameters.

Below are field test that usually carried out and also laboratory test

i) Field Test

- Standard Penetration Test (SPT)
  - to collect the soil samples in order to determine soil strata for the proposed area and also to collect undisturbed samples for laboratory test

- Piezocone / Cone Penetration Test (CPT)
  - to obtain undrained shear strength, which basically only used for soft soil.

- Field Vane Shear Test
  - to obtain undrained shear strength, which basically only used for soft soil.

ii) Laboratory Test

- Particle Distribution Test
  - to obtain the soil classification. Particle size distribution is one of the most important physical characteristics of soil. Many foundation

properties are closely related to particle size, such as probable soil behavior, soil description and classification.

- Atterberg Limit
  - to obtain plasticity limit, liquid limit and plasticity index. Plasticity is an important characteristic in soft soil especially fine-grained soils, because it's describing the ability of a soil to undergo unrecoverable deformation at constant volume without cracking or crumbling. For example, if there have a bearing capacity failure under the foundation, it wills permanently forming failure.

- Moisture Content
  - to determine the water content in the fine-grained soil such as silt and clay. The result obtained is useful in determine the overall view of soil's deformation.

- Chemical Test
  - to determine the pH, chloride, sulphate and organic content in the soil

- One Dimensional Consolidation Test
  - to obtain compressibility and consolidation parameters for settlement analysis

- Shear Strength Test
  - to determine strength parameters for stability and bearing capacity analyses of foundation.

For detailed of the above-mentioned field test and laboratory test, refer to the Design Guideline at Appendices.

4.2.4 Soil Data

Soil data required in the design will be obtained from the above- mentioned field and laboratory test. These data are usually determined either directly from the test result or need some interpolation or correlation. In the chapter 6 of the design guideline attached at the Appendix, explanation on how to get the data from the test result are provided.

Based on the flow chart above, below are the soil data that required with representative value for each types of soil:

i) Young's modulus of soil, E_s

Young's modulus is commonly used for estimation of settlement from static loads. There are few methods to obtain Young's modulus of soil, and as stated below:

- Empirical correlations from undrained shear strength, c_u
- Laboratory tests on cohesive soil
- Field tests which are Standard Penetration Test (SPT) and Piezocone Test (CPT)

Table 4.1: Representative values of Young's modulus, E_s

Type of soil	Es (MN/m²) static	Es (MN/m²) dynamic
Noncohesive soils		
- Sand, loose,round	40-80	150-300
- Sand, loose, cornered	50-80	150-300
- Sand. Medium dense, round	80-160	200-500
- Sand, medium dense,cornered	100-200	200-500

- Gravel without sand	100-200	300-800
- Crushed stone, sharp edged	150-300	300-800
Cohesive soils		
- Clay, hard	3-50	100-500
- Clay, semistiff	6-20	40-150
- Clay, stiff	3-6	30-80
- Loam, glacial clay	6-50	100-500
- Loam, loess loam	4-8	50-150
- Silt	3-8	30-100
- Silt, sea silt, organic	2-5	10-30

ii) Poisson's ration, v_s

A standard procedure to evaluate the value of Poisson's ratio, v_S does not exist. Poisson's ratio for soil usually varies from 0.25 to 0.49. Below is the representative value for each type of soil.

Table 4.2: Representative values of Poisson's ratio of soil, v_s

Types of soil	v_S
Unsaturated clay	0.1 – 0.3
Saturated clay	0.4 – 0.5
Sandy clay	0.2 - 0.3
Silt	0.3 – 0.4
Sand	0.2 – 0.4
Rock	0.1 – 0.4

iii) Shear modulus of soil, G_s

Shear modulus of soil, G_s is used for settlement analysis and obtained from the dynamic load test. Below is the representative value for each type of soil.

Table 4.3: Representative values of Shear modulus of soil, G_s

Type of soil	$G_s(MN/m^2)$
Noncohesive soils	
• Sand, loose	50 – 70
• Sand, medium dense	70 – 170
• Gravel with Sand, dense	100 – 300
Cohesive soils	
• Silt, sea silt	3 – 10
• Loam, soft to stiff	20 – 50
• Clay, semistiff to stif	80 – 300
Rock	
• Stratified, brittle	1000 – 5000
• Solid	4000 – 20 000

iv) Undrained shear strength parameters, c_u

Undrained shear strength,c_u is one of the parameters obtained from shear strength test. It is also known as total stress parameter. The parameter can be obtained directly and indirectly from laboratory testing which are:

- Unconfined Compression Test (UCT)
- Unconsolidated Undrained Triaxial Test (UU)

Field test that can be used to determine c_u are:

- Standard Penetration Test (SPT)
- Piezocone Test
- Vane Shear Test

Below is the representative value of c_u for each type of soil:

Table 4.4: Undrained shear strength, c_u classification

Consistency of clay	Undrained shear strength (kN/m^2)
Very stiff or hard	>150
Stiff	100-150
Firm to stiff	75 - 100
Firm	50 - 75
Soft to firm	40 -50
Soft	20 - 40
Very soft	<20

***Reproduced from BS 8004: 1986**

4.2.5 Pile and Raft Data

In the design, data from pile and raft are also needed, such as:

Pile

- Young's Modulus, E_p
  - based on pile load test
- Radius of pile shaft, r_o
- Pile length, L_p – based on the design
- Pile diameter, d – RC pile, with size normally 150mm to 200mm
- Pile spacing, center to center, s – minimum spacing is 3d

Raft

- Young's Modulus, E_r
  - For the raft thickness between 100mm to 600mm, the range of Young's modulus is 2500 GPa to 3600 GPa
- Poisson's ratio, v_r
  - A common value for Poisson's ratio of a raft is 0.3.
- Raft dimensions; width and length (depend on the base area of the structure)
- Raft thickness

These data will used in the formula given in the literature review. The analysis part and calculation will be explained in chapter 8.

4.2.6 Calculation

The final staged in the piled raft design is analysis and calculation. From this analysis, we will determine whether the designed foundation is accepted or not in term of total settlement and differential settlement. In the final staged, we will cover:

- Calculation of number of piles and spacing required
- Calculation of soil's, raft and pile bearing capacity
- Calculation of raft and pile group stiffness
- Calculation of average settlement and differential settlement
- Calculation of load distribution between raft and piles

4.2.7 Analysis

4.2.7.1 Friction pile

Friction pile and end-bearing pile are different in its function, where end-bearing pile is used to transmit the load to a stratum or hard layer or bed rock. When a friction pile subjected to a downward vertical load, the transfer of load to the surrounding soil is entirely by the shear at the interface. As the structure goes down due its settlement, the shaft friction of the pile will produce upward forces to resist the settlement. In settlement of friction piles, the settlement in predicted on the assumption that the net load from the structure is transferred to a depth to two – thirds the pile length and that dispersion of the load takes places into soil from this level.

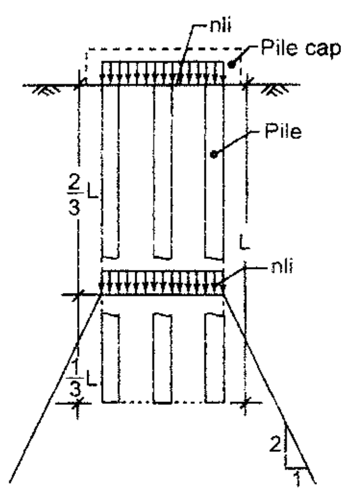


Figure 4.2: Load transfer in friction pile

The bulb of pressure for the friction pile are along its surfaces area, so there will less concentration of load in friction pile compare to end-bearing pile, where the bulb of pressure will be at the tip of pile. Therefore, the spacing for the friction should be consider the bulb of pressure, because a sufficient spacing in necessary in order to avoid inference between adjacent friction piles. Whereas in end-bearing pile, since the bulb of pressure under the tip of pile, the spacing of piles can be less that friction piles which is 2.5d.

4.2.7.2 Settlement

The settlement of the piled raft is depending on the stiffness of the raft and also piles stiffness. The magnitude of shaft friction of pile is linearly proportional to its length; therefore longer of friction pile can reduced the settlement more. Thicker raft may also contributed to the less of settlement, due to pile-raft interaction, where the weight of the raft will produce a contact pressure with the soil. This pressure will increase the in-situ stress of subsoil, thus increase the magnitude the negative skin-friction along the pile shaft. So, settlement will be less.

4.2.7.3 Differential settlement

In order to achieve an ideal piled raft as differential controller, the required pile that required may be estimated by consideration of the 'ideal' contact pressure distribution that acts beneath a rigid raft. At the central of raft, the contact pressure is approximately half of the average applied pressure. Therefore, the number and the length of piles at the center should be higher than other part of the raft. Thus, it will give minimal differential settlement.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As conclusion, this design guideline will guide and help user especially UTP students in understanding and learning how to design the piled raft foundation. It is a good opportunity for the student itself because this foundation is become popular in foundation construction on soft soil area.

This guideline will help the user in calculation staged because it can be done manually without used of any engineering software. A spreadsheet will be also attached together with the guideline.

5.2 Recommendation

For the safe and economic design of piled raft, it is necessary to use methods of analysis which have the capacity to consider all relevant design consideration, which are:

- Bearing capacity
- Total settlement
- Differential settlement
- Load distribution between pile and raft

Future research can be done by:

- Extending the scope of the guideline to the other type of soil such as sand, limestone and etc. This is because, piled raft is not only for soft soil area but also can be used for different soil condition.

- Developing design guideline for other types of structure such as tall building. In this project, we only focus on small structure such as houses, so further research can focus on other structures.

- Developing a design guideline that used software to design the foundation. By using software, better and more detailed analysis can be done. It is very essential if the students can learn how to design using the software.

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UNIVERSITI
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DESIGN GUIDELINES FOR PILED RAFT FOUNDATION

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FOREWORD

It gives a great pleasure to write this foreword and I would to thank to anyone that used this guideline as their reference. This design guideline of piled raft foundation is a comprehensive in its coverage and it's already sufficient for the beginner to get some idea and view about the design.

Readers will be explained regarding the piled raft design from the early phase until it final phase, which is from site investigation to design calculation and analysis. It is important to bear in mind that, this guideline is only a compilation of design guideline and using simple hand calculation in the design calculation.

This method only can be used for learning purposes and also can be as preliminary stage. It is because, the values given only an estimated data. Sufficient engineering software like SAFE is required to do the actual design and the step to design the foundation will be different. The basic steps are still same, only the design step in calculation will be different.

In this guideline, its only focus on the used of piled raft for the soft soil area which clays and suitable for construction of foundation for houses. An engineering spreadsheet will be provided to help the user in design calculation, and a manual how to use the spreadsheet will be also attached together.

For the user, who want get more information about particular section in this guideline, please refer to the reference given in the references column for more detail.

It is great hope that readers can get something from this guideline and can have some idea about what is piled raft is all about and how to design it.

ACKNOWLEDGEMENT

I wish to express thanks to AP Dr Indra Sati Hamonangan Harahap for helping me in this compilation of design guideline for piled raft foundation. His assistance help more in completing this guideline.

I want acknowledge and thank to G&P Geotechnics Sdn. Bhd for making this project possible. Their contribution range from providing necessary information regarded piled raft design such as articles, journals and also a design guideline for piled raft foundation as my references.

Also not to be forgotten, thank you to anyone that have give contribution in this project directly or indirectly.

References

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Every civil engineering structure, whether it is a building, bridge or any structure, it will have a foundation under it or below the structure. The function of foundation is to receive the load from the structure and transfer it to the soil or bed rock. There many type of foundation that be used in the construction with regard to its soil condition.

Piled raft foundation is one of the foundations that already used in other country, but it can be said that it is still new in Malaysia. Piled raft foundation is being used widely nowadays, due to its advantages in construction field. This foundation is effective in minimizing the total and differential settlement, improving bearing capacity of a shallow foundation, and reducing internal stress and bending moment within the raft.

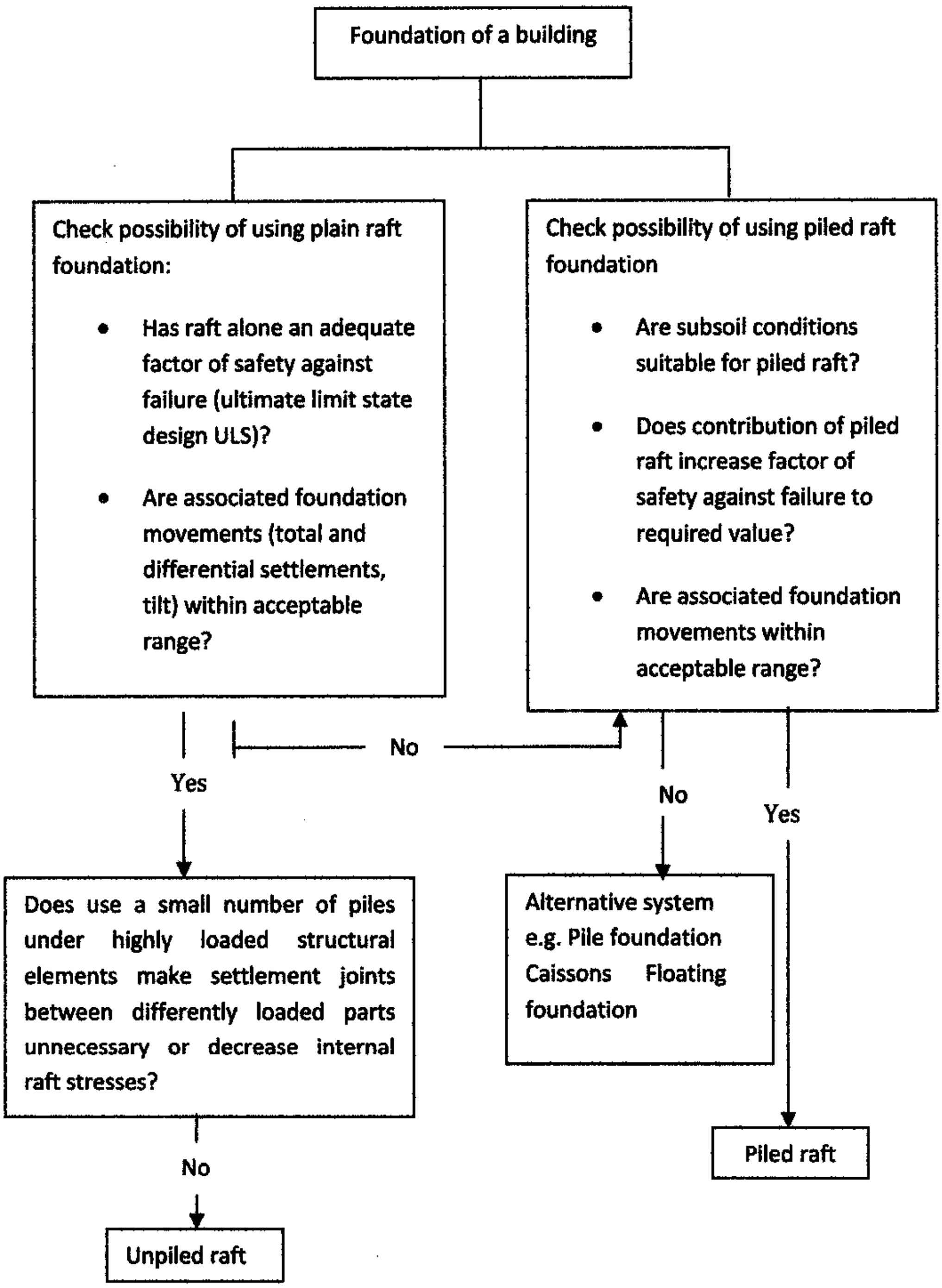
Piled raft foundation is consists of raft, pile and soil. The load from the structure will be shared between raft and piles and piles will also act as settlement controller. Current design of piled raft has ignored any contribution from the raft to carry part of the total load from the structure. The piles are designed to carry the total load and from economic perspective, this approach is uneconomical and conservative. The foundation designed in such a way often required more piles than are necessary.

Theoretically, for optimum design, the role of raft had to be taken into consideration. But in construction perspectives, taken load-sharing between raft and piles will cause the construction of foundation becomes crucial. An intensive construction controlling should be done during construction to make sure that the raft has contact pressure with soil. This is because, to make the raft took some load, it must have direct contact with the soil, so the contact pressure can be formed.

As explained in the introduction, raft transmitted the load through contact pressure with soil, but if there no contact with raft and soil, raft can't transfer the load.
If there have the gap between the raft and soil due to several factors, for example the error during construction execution or the soil beneath the raft is settled, contact pressure between raft and soil would not happen.

That why, most of the designer neglected the role of raft and assumed the piles taken 100% of the load, due to its crucial construction method. This also to take a safe method, because if the there have the problem with raft's function, it will not affect the structures because the piles are already designed to take 100% of the load. Role of raft can be considered, but it needs crucial construction method and controlling during construction. But, the guideline still focused on the load-sharing in the design calculation for education purposed.

2.1 Selection procedure for design of plain and piled raft foundations



3.1 Design Approach

According to Randolph (1994), three (3) design approaches can be used in piled raft. However, only two (2) approaches are discussed which are:

i. Conventional Approach
   In this approach, the foundation is designed as a pile group, with regular spacing of the piles over the complete foundation area. The foundation will make an allowance for the load transmitted directly from the raft to the soil. Thus, that will be a reduction in number of piles, due to perhaps only 60-75% of the total load being carried by the piles.

ii. Differential Settlement Control Approach
   In this approach, the conventional approach will adopts a uniform distribution of piles beneath the raft. The primary aim is to control the total settlement to an acceptable amount. The differential settlement will be reduced as the total settlement is reduced. The pile is designed to act as settlement controller through its shaft friction.

Both approaches discussed above are only applicable where the piles capacity is achieved primarily through shaft friction and not end bearing i.e. friction piles.

3.1.1 Raft

There are basically two approaches have been suggested for analyzing the behavior of raft, which are as below:

1. Rigid foundation approach
2. Flexible foundation approach

1. Rigid foundation approach

   In this approach, the raft is assumed to be rigid enough to bridge over non-uniformities of the soil structure. The pressure distribution under the raft is considered to be either uniform or varying linearly. The advantage of this approach is differential settlements are comparatively low but it will lead to higher bending moment and shear forces in the raft. This approach can be designed by adopted thicker raft.

2. Flexible foundation approach

   In this approach, the raft is considered to distribute load in the area immediately surrounding the column depending on the soil characteristics. The advantage of this approach is bending moments and shear forces in the raft is comparatively low but the differential settlement will be higher. This approach can be designed by adopted thinner raft.

In this guideline, we will use the rigid approach in the design calculation.

3.1.2 Pile

Normally, in the practical design of piled raft foundation for houses or shop lot, RC square pile will be adopted with size of between 150mm to 200mm. In the special case, spun pile with diameter of 300mm to 500mm can also be adopted.

3.2 Design Consideration

There are a few aspects that are taken into consideration in the design. For the safe and economic design of piled raft, it is necessary to take all the aspects explained below, which have the capacity to consider all relevant pile-raft-soil interactions :

1. Load-settlement behavior of the piled raft, both total settlement and differential settlement.
2. Load sharing between raft and the piles.
3. Bending moments and shear forces for the structural design of the raft and piles.

3.3 Procedure to design piled raft foundation

Piled raft foundation

↓

Soil investigation

To obtain soil parameters required in the design

Filed Test

1. Standard Penetration Test (SPT)
2. Cone Penetration Test (CPT)
3. Vane Shear Test

Laboratory Test

1. Particle Size Distribution Test
2. Atterberg Limit
3. Moisture content
4. Chemical test
5. One-dimensional Consolidation Test
6. Shear strength test

↓

Preparation of information

- Structural column locations and loading plan
- Raft, pile and soil parameters

↓

Structural layout
Column location and load
(dead load + live load)

↓

Raft's parameters required

1. Young's Modulus, E_r
2. Poisson's ratio, v_r
3. Raft dimensions; width and length (depend on the base area of the structure)
4. Raft thickness

↓

Pile's parameters required

1. Young's Modulus, E_p
2. Pile length, L_p
3. Pile diameter, d
4. Pile spacing, center to center, s
5. Number of piles, n

↓

Soil's parameters required

1. Young's modulus of soil, E_s
2. Poisson's ration, v_s
3. Shear modulus of soil, G_s
4. Undrained shear strength, c_u

↓

Interpolate the soil's parameters from filed test and laboratory test

↓

Design the piled raft

Calculation and analysis using Simple Calculation Method

i) Number of piles and spacing
ii) Bearing capacity for piled raft
iii) Raft stiffness
iv) Pile group stiffness
v) Piled raft stiffness
vi) Average settlement for the piled raft
vii) Differential settlement for the piled raft
viii) Load distribution between raft and pile

4.1 Purpose of Subsurface Exploration

"Subsurface exploration" is a process of identifying the characteristic of the subsoil at the project site, such as type of the subsoil underlies the proposed site. The information that collected from the exploration will help or guide the engineer to:

1. Selecting the type of foundation.
2. Estimating the load-bearing capacity of the foundation.
3. Estimating the possible settlement of the structure and foundation.
4. Determining the location of the water table.
5. Determining potential foundation problem that could happen such as collapsible soil.
6. Establishing constructions methods.

4.1.1 Site Investigation (SI)

During this stage, a few field tests will be carried out at the project site, which are consists of making test boreholes and collecting sample at specified interval of depth. The depth interval can be changed during the drilling operation, depending on the subsoil encountered. The selection of the boreholes will be decided by the engineer and normally it will depend on the topography of the proposed site. In the foundation design in soft clay, the main consideration is settlement, so a few in-situ tests or field test will be carried in order to obtain the soil settlement parameters. Below are the field tests carried out to obtain the parameters required in the piled raft foundation design. Beside the tests explained below, there are also other tests that may be carried out for other purposed, which not will cover in this guideline.

4.2 Standard Penetration Test (SPT)

Standard Penetration Test (SPT) is most commonly used in-situ test in Malaysia. During this test, a borehole will be drilled .Boreholes are sometime called deep boring. Borehole usually includes boring through soil, coring through rock, sampling in-situ testing and water table observations. The most common method of drilling the borehole is rotary open hole drilling by circulating fluid which water. Normally a chemical fluid will be added into the water as stabilization material, to stabilize the borehole wall from collapse during the drilling. Most common stabilization fluid is bentonite or air foam.

SPT is generally carried out at 1.5m depth interval or larger interval depending on the undisturbed soil sampling schedule. When the drilling rod reaches the specified interval, a sampler will be driven to collect the sample at a total penetration of 450mm into soils and the number of blows for the last 300mm of penetration is the SPT'N value.
Soil samples collected from the borehole are as follows:

- Disturbed Soil Samples: from split spoon samplers after SPT.
- Undisturbed Soil Samples: using piston sampler, thin wall sampler or mazier sampler.

Refer to Figure 4.1 and 4.2, to see the picture of borehole rigs and samplers.

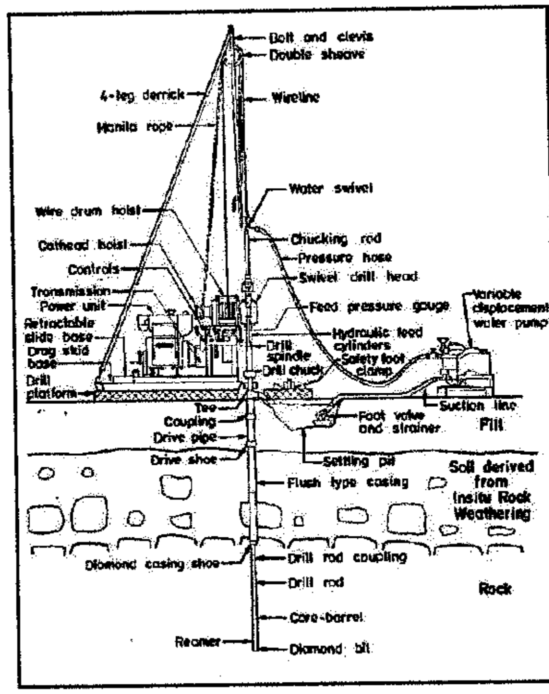


Figure 4.1: Typical Rotary Drilling Rig

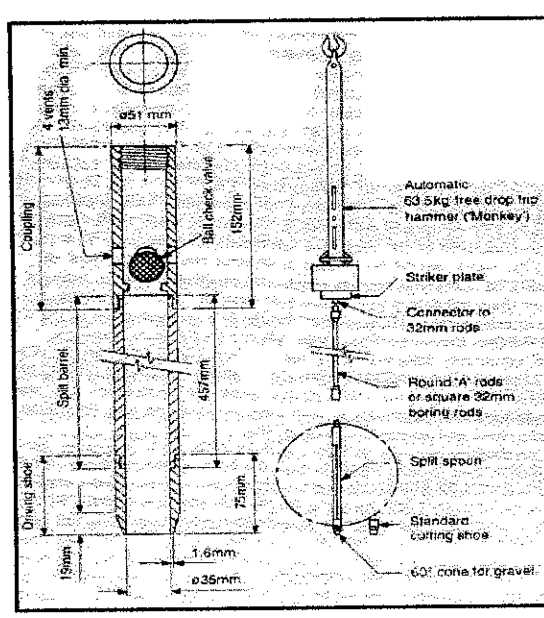


Figure 4.2: Sampler for SPT

Piston sampler is used for very soft to soft cohesive soil (SPT'N< 2). For cohesive soils from soft to firm, thin wall can be used (SPT'N<10) and for stiff soil which is SPT'N value > 10, mazier sampler will be used. The diameter of the piston sampler, thin wall and mazier are 75mm and length of 1 meter. For collecting undisturbed sample, it good to obtain 1m long sample but sometimes it is difficult, because it depend on the soil's condition.

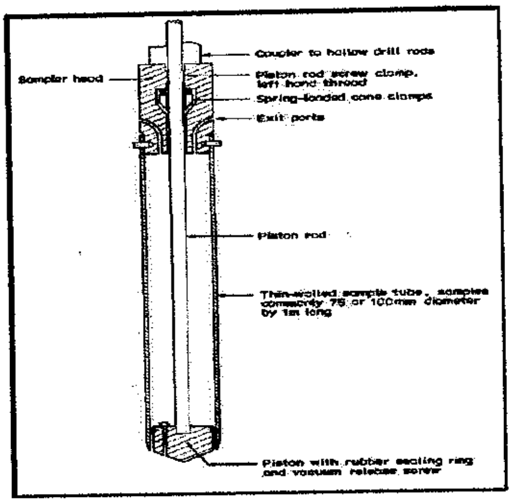


Figure 4.3: Piston Sampler

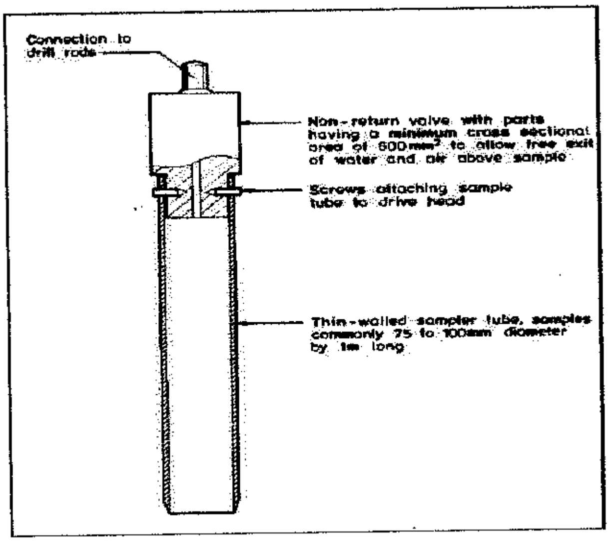


Figure 4.4: Thin Wall

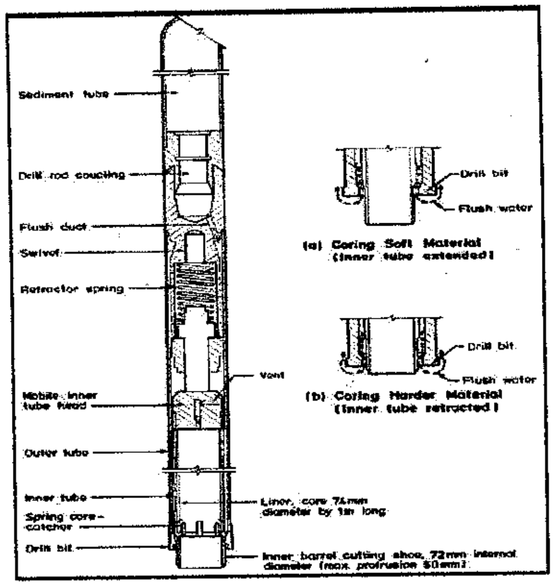


Figure 4.5: Mazier Sampler

Disturbed samples that been collected will be putted into the plastic bag and for undisturbed sample, soil sample will remain inside the sampler and it will be sealed with non-shrink wax. The purposed is to prevent the loss of moisture. It is important to maintain the in-situ condition of the soil because these samples will be sent to laboratory for testing.

Other than its main purposed as collected soil sampling, there are also other applications of SPT results in international geotechnical design.

Derivation of geotechnical parameters
• Angle of shearing resistance of cohesionless soils • Undrained shear strength of clays • Modulus of elasticity or stiffness coeffiecient, respectively, of cohesionless and cohesive soils • Maximum shear modulus

Table 4.1: Derivation of geotechnical parameters from SPT

Direct calculations
• Settlements of spread foundations on sand • Acceptable bearing pressure of foundations on sand • Acceptable bearing pressure of rafts on sand • Shaft and end resistance of piles • Sheet pile ability

Table 4.2: Direct calculations from SPT

4.3 Piezocone / Cone Penetration Test (CPT)

Piezocone (CPT) has three main applications which are as below:

- To determine subsoil stratigraphy and identify materials present.
- To estimate geotechnical parameters.

See Figure 4.6 for figure of typical piezocone rig.

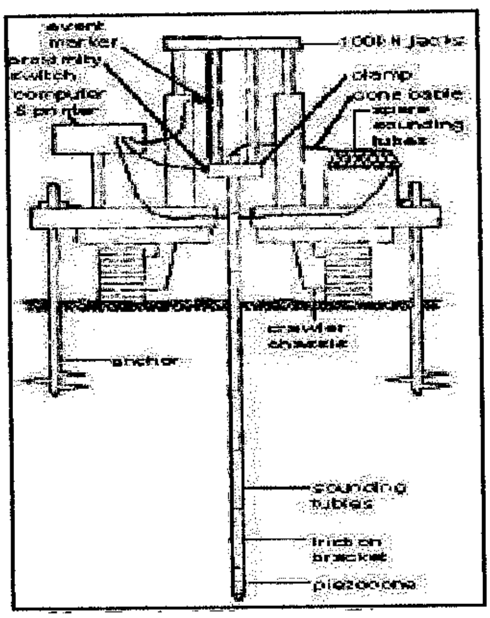


Figure 4.6: Typical Piezocone rig

Based on the Figure 4.7 below, it shows the design features of the piezocone. The cone is the cone-shaped end piece of the penetrometer tip on which the end bearing is developed. The diameter of the cone is normally 35.7mm, area of $10cm^2$ and cone angle of 60^o.

The friction sleeve is part, where the local side friction resistance is been measured. It has an area of 150cm2, diameter of 35.7mm and is slightly larger that the cone. The pressure sensor is used to measure the pore water pressure. All the data are captured electronically on computer. Piezocone is normally used for soft clay because the cone tip cannot penetrate into hard or stiff layer

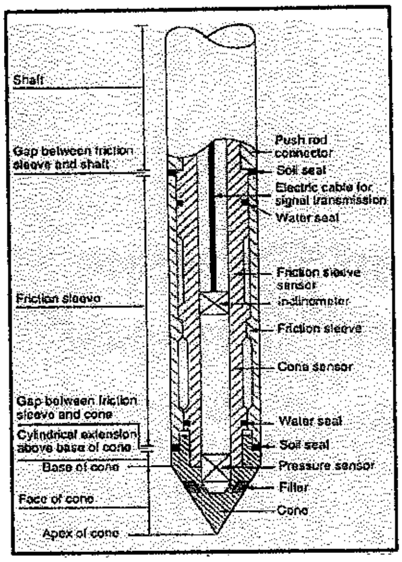


Figure 4.7: Detailed Terminology of Piezocone

This test is carried out to obtain settlement parameters, because at soft soil area settlement is main consideration.

Using some correlation with the soil parameters obtained from the test, below are the parameters that can be determined:

- Undrained Shear Strength, c_u
- Effective Angle of Friction, Φ
- Secant Young's Modulus, E_s
- Maximum Shear Modulus, G_s

4.4 Field Vane Shear Test

Field vane shear test is usually used during soil investigation operation to measure 'undisturbed' peak undrained shear strength (c_u), and remoulded undrained shear strength thus sensitivity of the soil. Field vane shear tests are economical and give good results in soft to medium stiff clays. The vane shear apparatus consists of four blades on the end of a rod, as shown in Figure 4.8 below.

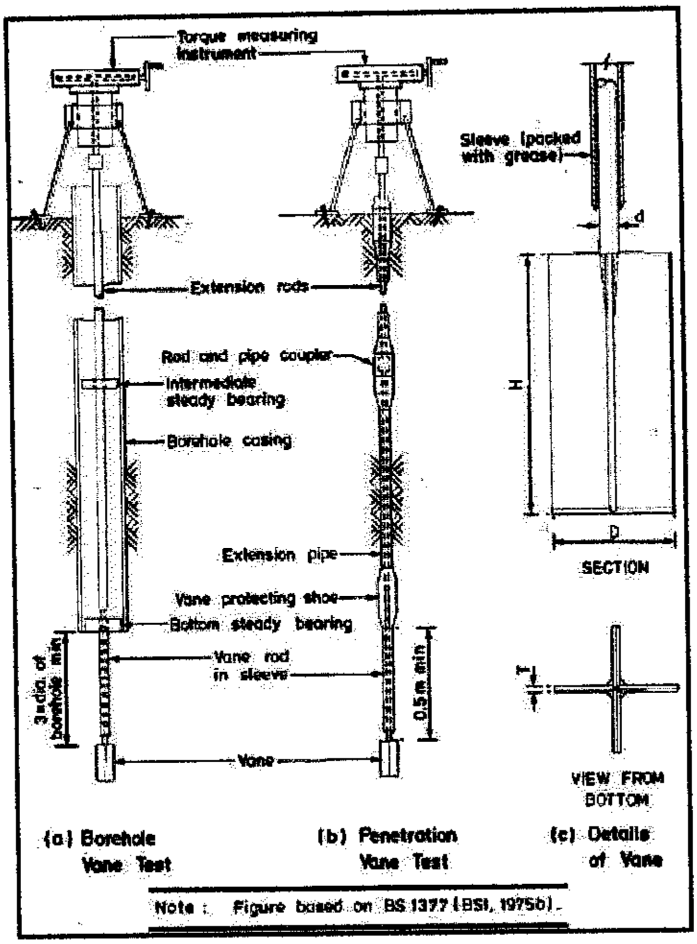


Figure 4.8: Field Vane Shear Device

In previous chapter, we already learned about a few field tests that commonly carried out before a particular construction started. For this chapter, we will discuss about the types of laboratory test that also commonly used in Malaysia. The objectives of laboratory test are:

1. To determine the subsoil layer characteristic whether its sand, silt, clay or etc.
2. To obtained soil properties and characteristic.

Laboratory test scheduled will be done first before sending the soil samples to the laboratory. This scheduled is used to select particular soil sample based on its length of sample collected and its types whether disturbed or undisturbed sample. Usually, not all the samples will be sent to laboratory because it is costly. Only a few samples will be tested. Refer to the Appendix A, Table 5.1 for the example of laboratory test scheduled.

Below are the most common laboratory test carried out and soil sample used for foundation design:

LABORATORY TEST	SOIL SAMPLE
Particle Size Distribution • Sieve Analysis – for content of sand and gravels) • Hydrometer Tests – for content of silt and clay	Disturbed sample
Atterberg Limits • Liquid limit (LL) • Plasticity Limit (PL) • Plasticity Chart – used in Plasticity Chart for soil classification)	Disturbed sample
Moisture Content	Disturbed sample
Chemical Test • pH Test • Chloride Content Test • Sulphate Content Test • Organic Content Test	Disturbed sample
One Dimensional Consolidation Test – to obtain compressibility and consolidation parameters for settlement analysis.	Undisturbed sample
Shear Strength Test • Isoptropic Consolidated Undrained Triaxial Test (CIU) • Unconfined Compression Test (UCT)	Undisturbed sample

Table 5.2: Laboratory Testing

5.1 Particle Size Distribution

Particle size distribution is one of the most important physical characteristics of soil. Many foundation properties are closely related to particle size, such as probable soil behavior, soil description and classification. The size of soil particles varies roughly from 0.0001 to 200 mm.

Particle size over 0.06 are determined by sieving, the fines, smaller than 0.06mm, are subdivided by hydrometer test.
In this test, we can obtain information about the soil strata and also the depth of soft soil layer. This information will be used to determine, for example pile length.

Based on British Soil Classification, we can determine the soil classification. Refer Appendix A Table 5.3 to see table of British Soil Classification System for Engineering Purposes.

5.2 Atterberg Limit

In case of fine-grained soils, any chance in water content brings out a change in engineering properties. With decreasing water content, deformability (plasticity) of clayey soils becomes lower, while strength increases because the net attractive forces between particles will increase. Depending on its water content in the soil, a soil may exist in the liquid, plastic, semi-solid or solid state. For a soil to exist in the plastic state, the magnitudes of the net inter particle forces must be such that the particles are free to slide relative to each other, with cohesion between them being maintained.

Most fine-grained soil exists naturally in the plastic state. The upper and lower limits of the range of water content over which a soil exhibits plastic behavior are defined as the liquid limit (w_L) and plastic limit (w_P). From these two values, we can calculate the plasticity index (I_p) of the soil.

$$I_P = w_L - w_P \qquad (5.1)$$

Plasticity is an important characteristic in soft soil especially fine-grained soils, because it's describing the ability of a soil to undergo unrecoverable deformation at constant volume without cracking or crumbling.For example, if there have a bearing capacity failure under the foundation, it wills permanently forming failure.
Based on plasticity chart in Appendix A, Figure 5.1, we can whether the fine-grained soil is low plasticity, intermediate plasticity, high plasticity or extremely high plasticity. This chart are taken from British system (BS 5930: 1981)

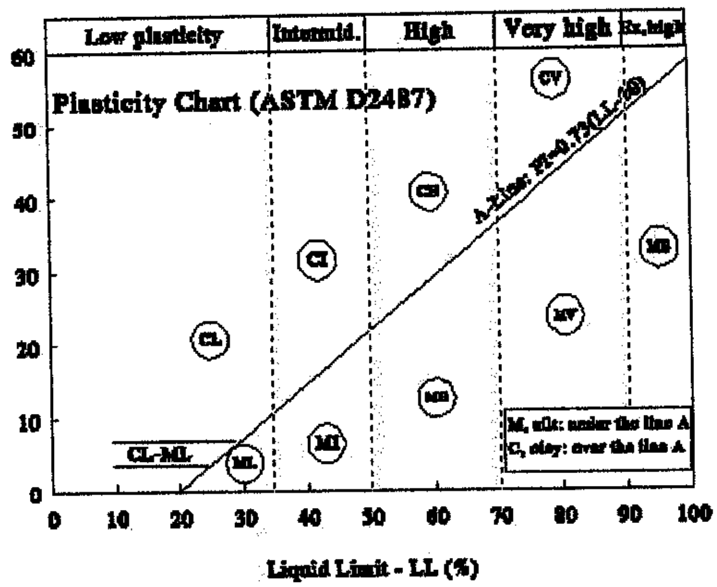


Figure 5.1: Plasticity Chart

5.3 Moisture Content

Moisture content or water content, w is defined as the ratio of the mass of water Mw to the mass of solids Md

$$w = \frac{M_W}{M_d} \qquad (5.2)$$

This test is usually conducted to determine the water content in the fine-grained soil such as silt and clay. The result obtained is useful in determine the overall view of soil's deformation.

5.4 Chemical Test

Chemical test is carried out to determine four important element:

- Ph
- Chloride content
- Sulphate content
- Organic content

pH test is to determine the pH value for soil layer. It is important to know whether the soil is acidity or not, because it will affect the foundation especially the concrete. Sulphate content is the single most dangerous source which can disrupt. It is important to take note about the sulphate content in the soil and ground water. Chloride content is other dangerous sources in soil, because it can corrode the embedded steel.

5.5 One- dimensional Consolidation Test

Consolidation is gradually reduction volume of a fully saturated soil of low permeability due to drainage of some of the pore water. Due to the settlement is being our main priority, this test must be carried out.

One-dimensional Consolidation test is carried out to obtain compressibility and consolidation parameters for settlement analysis.
The characteristic of a soil during one-dimensional consolidation can be determined by oedometer test.

Some of consolidation parameters that we obtained from the test:

- Overconsolidation ratio (OCR)
- Recompression index (Cr)
- Compression index (Cc)
- Consolidation coeffiecient (Cv)

These consolidation parameters allow engineer to evaluate deformation of the subsoil when there is changes of stress in the subsoil.

There is also indirect estimation of the consolidation parameters from Atterberg Limit tests as follows. However the parameters for detailed design should be obtained directly from consolidation tests.

a) $Cc = 0.007(LL - 10\%)$ (5.3)
For normally consolidated clay, (Skempton, 1944)
b) $Cc = 0.009(LL - 10\%)$ (5.4)
For clays of low and medium sensitivity, (Terzaghi & Peck, 1967)

5.6 Shear Strength Test

Shear strength test is carried out to determine strength parameters for stability and bearing capacity analyses of foundation. The shear strength tests that are commonly used are as below:

i) Unconfined Compression Test (UCT), Unconsolidated Undrained Triaxial Test (UU) and Shear Box Test – for determine total stress parameter, which is undrained shear strength,c_u
ii) Isotropic Consolidated Undrained Trixial Test (CIU) – for determine effective stress parameters, which are c' and ϕ'.

In the previous chapter, we already learned about a few field and laboratory test that are commonly carried out in foundation design. For this chapter, we will focus on the soil parameters that are required in the design calculation of piled raft foundation. The design calculation will be explained in the Chapter 8 and it only applicable for preliminary stage. Detailed staged is not discussed in this design guideline and for more information about detailed staged, refer to the references given at the end of this guidelines. Below are the soil parameters that we required and it is obtain from interpretation and correlation of some of field and laboratory tests that already discussed above:

6.1 Elastic Young's Modulus

Young's modulus is commonly used for estimation of settlement from static loads. Suitable values of the elastic modulus Es as a function of depth may be estimated from empirical correlations from laboratory test results on undisturbed sample and result from field test

Laboratory tests that may be used to estimate the soil modulus are the triaxial unconsolidated undrained compression or the triaxial consolidated undrained compression tests. Field tests include the standard penetration test (SPT),
cone penetration test.

6.1.1 Empirical Correlations

The elastic undrained modulus E_s for clay may be estimated from undrained shear strength c_u by

$$E_s = K_C\, c_u \qquad (6.1)$$

Where;

E_s = Young's soil modulus

K_c = correlation factor, Figure 6.1

c_u = undrained shear strength

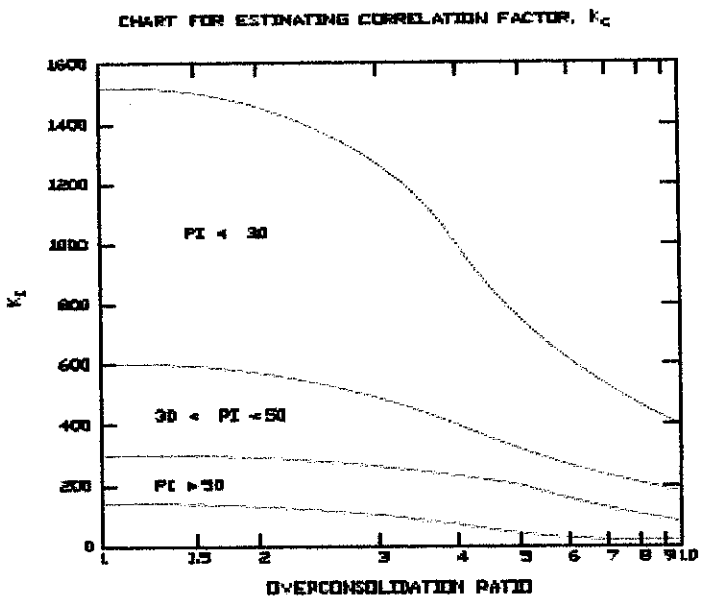


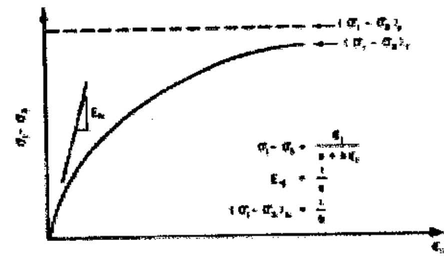
Figure 6.1: Chart for estimating constant K_c to determine soil Young's modulus.

6.1.2 Laboratory Tests on Cohesive Soil

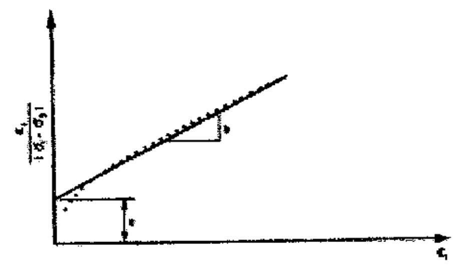
The young's modulus is sensitive to soil disturbance which may increase pore water pressure and, therefore decrease the effective stress in the sample and also reduced the stiffness.

- Triaxial unconsolidated undrained
  Using this test, an appropriate measure of E_s is the initial tangent modulus $E_{ti} = 1/a$, where a, is the intercept of a plot of strain/deviator stress versus strain. See Figure 6.2 below.

- Triaxial consolidated undrained
  Using this test, an appropriate measure of E_s is the reload tangent modulus that approaches the asymptotic value at large cycles. The tangent modulus at 1/2 of maximum applied stress is determined for each loading cycle and plotted versus the number of cycles. See Figure 6.3 below.

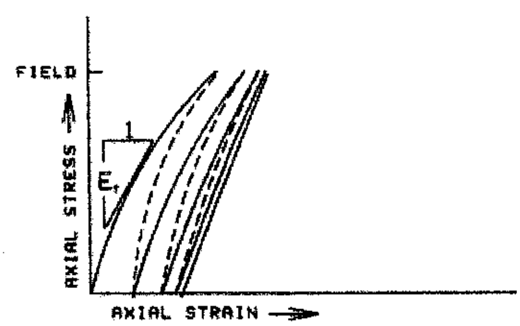


a. HYPERBOLIC RELATIONSHIP

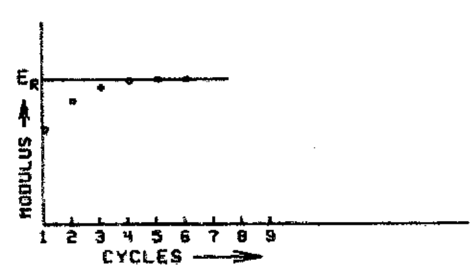


b. EVALUATION OF HYPERBOLIC PARAMETERS a, b

Figure 6.2: Hyperbolic simulation of stress-strain relationships



a. TANGENT MODULUS AT 1/2 MAXIMUM APPLIED STRESS



b. TANGENT RELOAD MODULUS VERSUS CYCLES

Figure 6.3: Elastic modulus from cyclic load tests

6.1.3 Field Tests

The young's modulus may be estimated from empirical and semi empirical relationship based on results of field soil tests.

- Standard Penetration Test (SPT)
  The elastic modulus in sand may be estimated directly by blow count by (item 60)

$$E_s = 9.4N^{0.87}\sqrt{B}\left(1 + 0.4\frac{D}{B}\right) \quad (6.2)$$

Where;
N = average blow count (SPT'N)
B = width of footing, m
D = depth of footing, m

6.1.4 Piezocone/ Cone Penetration Test (CPT)

The constrained modulus E_d has been empirically related with the cone tip bearing resistance by

$$E_d = \alpha_c \cdot q_c \quad (6.3)$$

Where;
α_c = correlation factor (Typical value for sands is 3 and for clays is 10)
q_c = cone tip bearing resistance

The above- mentioned details are empirical correlation examples to estimate E_s. Either method can be choosing to obtain the value. Below is representative value of Young's Modulus, E_s for each type of soil.

Table 6.1 : Representative values of Young's modulus, E_s

Type of soil	Es (MN/m^2) static	Es (MN/m^2) dynamic
Noncohesive soils		
- Sand, loose,round	40-80	150-300
- Sand, loose, cornered	50-80	150-300
- Sand. Medium dense, round	80-160	200-500
- Sand, medium dense,cornered	100-200	200-500
- Gravel without sand	100-200	300-800
- Crushed stone, sharp edged	150-300	300-800
Cohesive soils		
- Clay, hard	3-50	100-500
- Clay, semistiff	6-20	40-150
- Clay, stiff	3-6	30-80
- Loam, glacial clay	6-50	100-500
- Loam, loess loam	4-8	50-150
- Silt	3-8	30-100
- Silt, sea silt, organic	2-5	10-30

6.2 Shear Modulus, G_s

The shear modulus, G_s may be used for analysis of settlement from dynamic load. Shear modulus can be evaluated from dynamic tests. See Table 6.2 below to see representative value of shear modulus, G_s for each type of soil.

Table 6.2 : Representative values of Shear modulus of soil, G_s

Type of soil	$G_s(MN/m^2)$
Noncohesive soils	
• Sand, loose	50 – 70
• Sand, medium dense	70 – 170
• Gravel with Sand, dense	100 – 300
Cohesive soils	
• Silt, sea silt	3 – 10
• Loam, soft to stiff	20 – 50
• Clay, semistiff to stif	80 – 300
Rock	
• Stratified, brittle	1000 – 5000
• Solid	4000 – 20 000

6.3 Possion's Ratio, v_s

A standard procedure for evaluation of Poisson's ratio, v_s for soil does not exist. Poisson's ratio for soil usually varies from 0.25 to 0.49 with saturated soils approaching 0.49. Poisson's ratio for unsaturated soils usually varies from 0.25 to 0.40. A reasonable overall value for v_s is 0.40. Normal variations in elastic modulus of foundation soils at a site are more significant in settlement calculations than errors in Poisson's ratio. See Table 6.3 below to see representative values of Poisson's ratio, v_s

Table 6.3 : Representative values of Poisson's ratio of soil, v_s

Types of soil	v_s
Unsaturated clay	0.1 – 0.3
Saturated clay	0.4 – 0.5
Sandy clay	0.2 - 0.3
Silt	0.3 – 0.4
Sand	0.2 – 0.4
Rock	0.1 – 0.4

6.4 Shear strength parameters

Previously in Chapter 5, we already know that there are two (2) shear strength parameters which are:

- Total Stress
  - Like undrained shear strength, c_u required for short term undrained stability analysis of embankment on cohesive soils and for foundation design in cohesive soils.
- Effective stress
  - Like effective strength, c' and ϕ'are for long term stability analysis of foundation, embankment and slopes, particularly cut slopes.

For the design calculation in this guideline, we will only use undrained shear strength, c_u for calculation of bearing capacity of piled raft.

6.4.1 Undrained shear strength, c_u

Total stress parameters of undrained shear strength, c_u for cohesive soils can be obtained directly or indirectly from laboratory testing such as:

1. Unconfined Compression Test (UCT)
2. Unconsolidated Undrained Triaxial Test (UU)

Others are from correlations from field test such as SPT, Piezocone test and Vane Shear Test

6.4.1.1 Unconfined Compression Test (UCT)

Equation of Unconfined strength,qu

$$q_u = \frac{P}{A} \qquad (6.4)$$

Where;

q_u = unconfined compressive strength (kN/m^2)

P = compressive force (kN)
A = cross section of soil sample (m^2)

Since soils tend to deform much more than concrete, the area of the specimen changes to maintain constant volume through the test (bulging). Thus, the average cross sectional area at a particular deformation during the test is calculated using:

$$A = \frac{A_O}{1-\varepsilon} \qquad (6.5)$$

Where;
A = average cross-section area (m^2)
Ao = initial cross-section area(m^2)
$\mathcal{E}$ = axial strain ($\Delta L/L_o$)
ΔL = change in length, L = initial length (m)

Table 6.4: For relationship between N-value and unconfined compressive strength

N -value	Consistency	Unconfined compressive strength (kN/m^2)
<2	Very soft	<25
2-4	Soft	25-50
4-8	Medium	50-100
8-15	Stiff	100-200
15-30	Very stiff	200-400
>30	Hard	>400

Undrained shear strength, c_u

$$C_u = \frac{q_u}{2} \qquad (6.6)$$

6.4.1.2 Unconsolidated Undrained Trixial Tets (UU)

From the test, the failure envelope for the total stress Mohr's circles becomes a horizontal line and hence is called a f = 0 condition. Thus, we have

$$t_f = c = c_u \qquad (6.7)$$

Where;

c_u = undrained shear strength and is equal to the radius of Mohr's circles.

Note that the f = 0 concept is applicable to only saturated clays and silts.

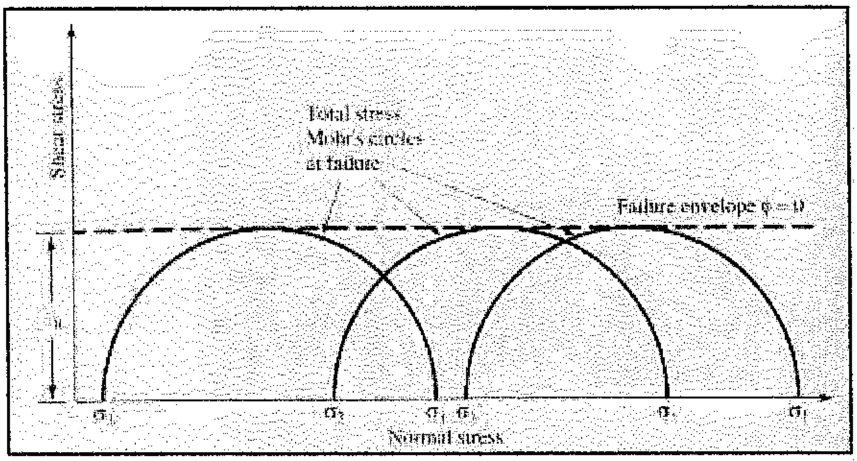


Figure 6.4: Total stress Mohr's circles and failure envelope (f=0) obtained from unconsolidated-undrained triaxial tests on fully saturated cohesive soil

6.4.1.3 Standard Penetration Test (SPT)

Below some correlations that commonly used to obtain undrained shear strength, c_u from SPT

For SPT'N > 5 (Stroud & Butler, 1975)
c_u =4N to 6N (kPa) (6.8)

For SPT'N < 5 (Japanese Road Association, 1980)
c_u = 5 + 7.5N (kPa) (6.9)

where N is SPT'N values

6.4.1.4 Piezocone Test

The undrained shear strength can be estimated from piezocone data with reasonably accuracy.

$$c_u = \frac{q_c - \sigma_{vo}}{N_k} = \frac{q_T - \sigma_{vo}}{N_{kT}} \quad (6.10)$$

Where;
σ_{vo} = total overburden pressure
q_c = cone resistance
q_T = corrected cone resistance
N_k or N_{kT} = cone factor

Cone factor, N_k is 14$\pm$4 for Malaysian Clay (Gue, 1998). In practice, the N_k and N_{kT} are determined empirically by correlation of cone resistance to undrained shear strength measured by field vane shear tests or laboratory tests.

6.4.1.5 Vane Shear Test

The undrained shear strength, c_u may be obtained directly from vane shear tests. Below is the equation that can be used to obtain c_u:

$$c_u = \frac{T}{\pi\left[\frac{d^2 h}{2} + \frac{d^3}{4}\right]} \quad (6.11)$$

Where;
T = torque at failure
d = overall vane width
h = vane length

According to ASTM (1994), if h/d = 2, then

$$c_u = \frac{T}{(366 \times 10^{-8}) d^3} \quad (6.12)$$

For indirectly indication the c_u, it can be obtained indicatively by correlating to result of Atterberg Limit Tests as follows:

a) $c_u/\sigma_v' = 0.11 + 0.0037\ PI$ (6.13)
   For normally consolidated clay, the ratio tends to increase with plasticity index (Skempton, 1957)
b) $c_u(mob) / \sigma_p' = 0.22$ (6.14)
   c_u(mob) is the undrained shear strength mobilized on the failure surface in the field, and σ_p' is the preconsolidation pressure (yield stress) (Mesri, 1988)

Table 6.5: Undrained shear strength, c_u classification

Consistency of clay	Undrained shear strength (kN/m^2)
Very stiff or hard	>150
Stiff	100-150
Firm to stiff	75 - 100
Firm	50 - 75
Soft to firm	40 -50
Soft	20 - 40
Very soft	<20

*Reproduced from BS 8004: 1986

7.1 Raft Dimension and Thickness

Raft dimension and thickness are depended on the structure the foundation supported and also the design approach, especially for raft thickness.

The width, B and length, L of the raft is normally depending on the base area of the structure. For example, if the base area of a link semi-D house is 20m X 6m, the width of the raft will be 20m and length is 6m. The dimension can be bigger than structure's base area depending on the design engineer.

The thickness of the raft is depending on the design approach, which is already explained in Chapter 3, Design Approach for Raft.
Raft's thickness also depending on the bearing capacity of the raft to support the load from structure. The calculation on the bearing capacity of raft will be discussed in the Chapter 8 later.

Based on the statement above, the raft thickness and dimension is mostly depending on the structural design of the building or the structure, which the base area of the structure and load from the structure.

7.2 Pile length and diameter

Pile length is normally based on the load from the structure and group skin friction that required in the design. It also based on the depth of the clay, if the layer is thick, the pile length will be longer but if it is thin layer, a shorter pile is already sufficient.

Pile length can be from 6m to 24m, and may be longer than that, depend on the design parameters, load from structure and soil condition.

Pile diameter, as explained in Chapter 3, it depend on the structure supported by the foundation. Normally, in the design practiced of piled raft foundation for houses or shop lot, RC square pile will be used with size, between 150mm to 200mm. In the special case, spun pile with diameter of 300mm to 500mm can be used.

7.3 Pile Spacing

Design the piled raft is same as designing a pile group consisting of individual piles with known cross section and length essentially means determining the layout of the pile group, which in others words means finding the pile spacing. Since friction pile is used in the design, the load will be transferred through the entire surface of the pile and bulb pressure is much larger in this case. See the Figure 7.1 below:

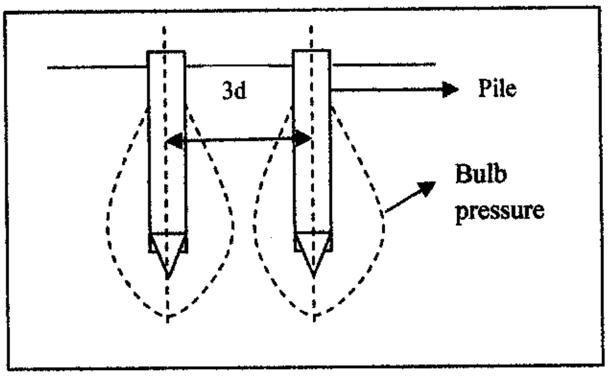


Figure 7.1: Bulb pressure of piles

Based on the figure above, a wider spacing becomes necessary in order to avoid interference between bulbs of pressure of adjacent piles. The minimum spacing center-to-center of piles is 3d or 3 times pile diameter. That is an ideal spacing for design layout of pile group.

7.4 Number of piles

Number of piles used in the design will be based on the column load and pile capacity. Usually in design, pile will be located below of the column and number of piles required can be obtained as below:

For example

Column load = 40kN
Pile capacity = 10kN

Number of piles
= Column load/ Pile capacity (7.1)

$$= \frac{40kN}{10kN}$$
$$= 4$$

7.5 Raft Young's modulus and Poisson's ratio

i) Young's Modulus, E_r

For the raft thickness between 100mm to 600mm, the range of Young's modulus is 2500 GPa to 3600 GPa

ii) Poisson's ratio

A common value for Poisson's ratio of a raft is 0.3.

7.6 Pile Young's Modulus

Young's modulus for a pile can be predicted from pile load test or other field test. Below is the simple calculation that can be used in determining the Young's modulus value for a pile:
From IS: 456-2000,Cl.5.2.3.1

$$E_p = 5000 \times \sqrt{grade\ of\ concrete} \qquad (7.2)$$

See in Appendix B, Worked Example 7.1 for determination obtain pile elastic Young's modulus from pile load test.

In this chapter, all the steps and calculations required in the design will be explained in details. But, remember these calculations are only used for preliminary stage, where we want to get an overall view of piled raft. The value that obtained from the calculation is only estimation value and can't be take as the accurate value for the design, for example the value for differential settlement. For detailed staged, engineering software has to use in order to obtain detail information about the design foundation.

Below are the steps of calculations that will cover in this chapter:

i) Number of piles required and spacing
ii) Bearing capacity for piled raft
iii) Raft stiffness
iv) Pile group stiffness
v) Piled raft stiffness
vi) Average settlement for the piled raft
vii) Differential settlement for the piled raft
viii) Load distribution between raft and pile

8.1 Number of piles required and spacing

Number of piles required can be determined by obtaining allowable load per load and the equation as below:

Allowable load per pile:

Surface area of piles
= d_p x no.of pile surface x L_p (Square pile = no of surface = 4) (8.1)

Where;
d_p = diameter of pile
L_p = length of pile

Allowable skin resistance

$$= \frac{q_u}{2} \times \frac{\alpha}{FS} \quad (8.2)$$

Where;
q_u = unconfined shear strength
α = reduction coefficient (Refer Figure 8.1)
FS = factor of safety

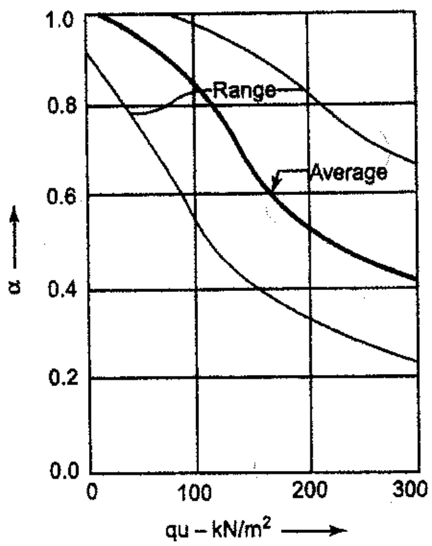


Figure 8.1: Friction pile in clay: α vs q_u

Allowable load per pile = Surface area of piles x Allowable skin resistance (8.3)

Number of piles required = Applied load / allowable load per pile (8.4)

Spacing
Minimum spacing = 3d

8.2 Bearing capacity of piled raft

In determining the bearing capacity of piled raft, the following equation can be used:

Based on the Terzaghi bearing capacity equation, bearing capacity of raft can be determined by

$$\text{Net bearing capacity} = c.\, N_c \qquad (8.5)$$

$$= \frac{q_u}{2}.\, N_c$$

where;

q_u = unconfined compressive strength

Nc = Terzaghi bearing factor

= 5.14 (continuos foundation)

For safety bearing pressure (sbp), a factor safety can be added into the equation as below:

$$\text{Sbp} = \frac{\text{net bearing capacity}}{F} \qquad (8.6)$$

$$= \frac{q_u.N_c}{6}$$

where;
F = factor of safety (F = 3)

To hold good for a footing of any rectangular shape, Eq. (8.2) can be modified by adding 'shape factor' into the equation. The Terzaghi bearing capacity factor N_c, according to Skempton, is influenced by both shape of the footing and its depth. As regards shape he considers the influence of the 'aspect ratio' (B/L), 'shape factor' is used because it is seen to be linear function of 'aspect ratio'.

$$\text{Sbp} = \frac{q_u N_c}{6} \times \left[1 + 0.2\frac{B}{L}\right] \qquad (8.7)$$

↓ shape factor

where;
B = width of raft
L = length of raft

Bearing capacity of raft
= Area of raft x sbp (8.8)

To obtain the bearing capacity of piled raft, we have to determine the pile group of surface shear and the equation used as follows:

Surface area
= (2B x L_p) + (2L x L_p) (8.9)

Allowable shear

$$= \frac{C}{F}$$

$$= \frac{q_u}{2.F} \qquad F = 3$$

$$= \frac{q_u}{6} \text{ x surface area} \qquad (8.10)$$

Piled raft bearing capacity
= Bearing capacity of raft + Allowable shear (8.11)

8.3 Raft stiffness

The average stiffness of a raft, acting alone may be estimated (Richard et., 1970) as:

$k_r = 4G_s r_0/(1 - \upsilon_s)$ for rigid circular raft (8.12)

$k_r = [G_s/(1 - \upsilon_s)]\beta_z(4cd)^{\frac{1}{2}}$ for rigid rectangular raft (8.13)

where;
r_0 = circular raft radius
β_z =coffiecient depending on the raft dimensions, c and d, given in Figure 8.1 below.

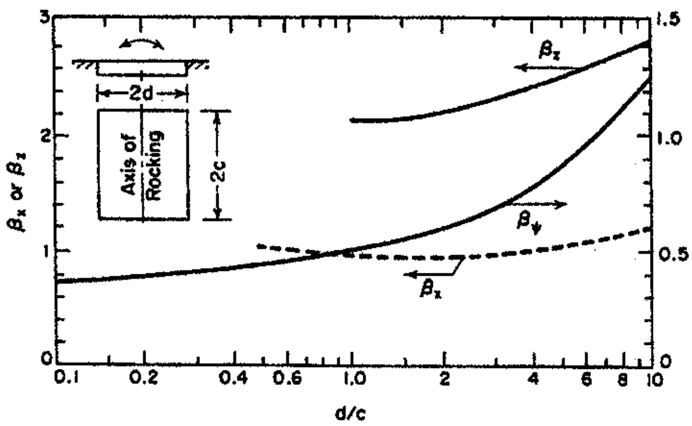


Figure 8.2: Coefficients β_z, β_x and β_ψ for rectangular footings (after Richart et al, 1970)

8.4 Pile group stiffness

8.4.1 Single pile stiffness

Stiffness of a single pile for compressible pile can be determined as follows:

$$\frac{P_t}{G_l r_o w_t} = \frac{\left[\frac{4}{1-v_s}\right]+\left\{\left(\frac{2\pi\rho}{\zeta}\right)\left(\frac{\tanh(\mu l)}{\mu l}\right)\left(\frac{L_P}{r_o}\right)\right\}}{1+\left\{\left(\frac{4}{\pi\lambda(1-v_s)}\right)\left(\frac{\tanh(\mu l)}{\mu l}\right)\left(\frac{L_P}{r_o}\right)\right\}} \qquad (8.14)$$

where;

$\frac{P_t}{w_t}$ = single pile stiffness

G_l = soil modulus at L_p

L_p = pile length

r_o = radius of pile shaft (D/2)

v_s = soil Poisson's ratio

ρ = vertical homogeneity of soil stiffness (G_{ave}/G_l)

ζ = measure of radius of influence of pile

= $\ln(r_m/r_o)$ $\quad r_m = 2.5\rho(1-v_s)L_p$

$r_m = 2.5\rho(1-v_s)L_p + 2.5d_p$ (very short pile range L_p/d_p <5)

μl = measure of pile compressibility ($\sqrt{(2/\zeta\lambda)}(L_p/r_o)$

λ = pile – soil stiffness ratio (E_p/G_l)

8.4.2 Pile Group Stiffness

Pile group stiffness can be calculated based on the principle of elastic interaction between piles. There are few methods that can be used and include as follows:

a) The 'efficiency' approach described by Fleming et al. (1992)
b) The equivalent pier approach described by Poulos and Davis (1980)
c) The interaction factor approach of Poulos and Davis (1980)

In this guideline, only first approach will be explained and used in the design.

8.4.2.1 Efficiency approach

Based on Fleming et al. (1992), pile group efficiency is

$$\eta_w = n^{-e} \qquad (8.15)$$

where;

n =number of piles

e = exponent

Exponent, e can be determined by using curve in Figure 8.2. The upper part of figure allows a base value of e to be chosen, depending on pile slenderness ratio. The four curves in the lower part, which are Poisson's ratio, υ_s homogeneity factor, ρ, spacing ratio, s/d, and stiffness ratio, E_p/G_l will modify the base value of e to get actual e.

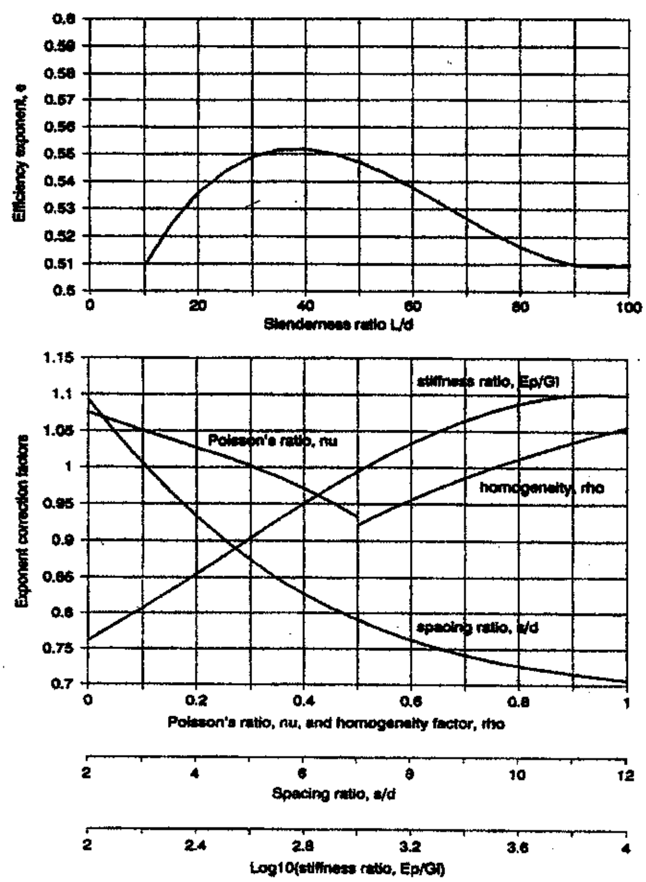


Figure 8.3: Charts for calculation of exponent e for efficiency of pile groups (after Fleming et al, 1992)

Pile group stiffness, k_p

$$= \eta_w n k_1 \qquad (8.16)$$

where;

k_1 = stiffness of a single pile

8.5 Piled raft stiffness

Randolph has been proposed a simple piled raft analysis which allows the overall stiffness load distribution of a piled raft to be calculated.

Piled raft stiffness, k_{pr}

$$= \frac{[k_p + k_r(1 - 2\alpha_{rp})]}{\left[1 - \alpha_{rp}^2\left(\frac{k_r}{k_p}\right)\right]} \qquad (8.17)$$

where;

k_p = pile stiffness

k_r = raft stiffness

α_{rp} = interaction factor

$$= \frac{In\,(\frac{r_m}{r_r})}{In(\frac{r_m}{r_O})} \qquad (8.18)$$

r_r can be determined by using $n\pi r_r^2$ = area of raft

8.6 Average settlement of piled raft

$$= \frac{applied\ vertical\ load}{piled\ raft\ stiffness} \qquad (8.19)$$

8.7 Differential settlement

Based on Randolph (1994), he expresses differential settlement as a proportion of the average settlement of the foundation and estimated using raft stiffness.

The raft-soil stiffness for rectangular raft, where $B \leq L$ can be defined by using the equation proposed by Horikoshi and Randolph (1997) and as below:

$$k_{rs} = 5.57\left(\frac{E_r}{E_s}\right)\left[\frac{(1-\upsilon_s^2)}{(1-\upsilon_r^2)}\right]\left(\frac{B}{L}\right)^{0.5}\left(\frac{t_r}{L}\right)^3 \qquad (8.20)$$

where;

E_r = Young's modulus of raft

E_s = Young's modulus of soil

υ_s = Poisson's ratio of soil

υ_r = Poisson's ratio of raft

t_r = raft thickness

B = raft width

L = raft length

By using the value of raft-soil stiffness ratio, the differential settlement can be calculated from the curves of Figure 8.4. From the curve, we will obtain normalized differential settlement, Δw. Thus, the differential settlement is as below:

$$= \Delta w \times \text{Average settlement} \qquad (8.21)$$

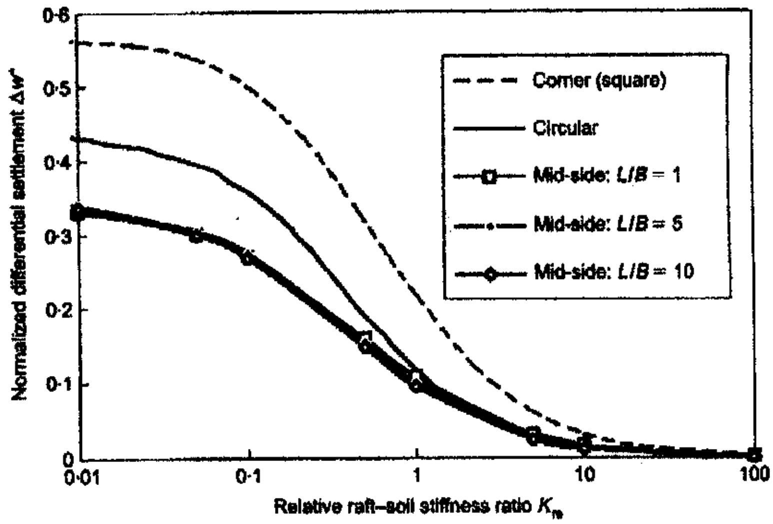


Figure 8.4: Variation of normalised differential settlement with raft-soil stiffness ratio, K_{rs} (after Horikoshi & Randolph, 1997)

The value that obtained from the above equation will be an unfactored value and to get factored differential settlement value, it can be calculated based on the equation below:

= unfactored value x (k_p/k_{pr}) (8.22)

Where;
k_p = pile stiffness
k_{pr} = piled raft stiffness

8.8 Load distribution between raft and pile

The proportion of load carried by the raft (P_r) and the pile group (P_p) is given by:

$$\frac{P_r}{(P_r+P_p)} = \frac{[k_r(1-\alpha_{rp})]}{[k_p+k_r(1-2\alpha_{rp})]} \qquad (8.23)$$

Refer to Appendix B, Worked Example 8.1 to get better understanding in the design calculations that have been discussed above.

Based on the design calculation done above, an analysis has to be conducted. The objective of this analysis is to determine whether the design piled raft can perform well in term of:

i. Piled raft bearing capacity
ii. Average settlement
iii. Differential settlement

9.1 Pile Raft Bearing Capacity

In the design, bearing capacity should be larger than average load or pressure from the structure. If the bearing capacity of piled raft is lower than the average load, the design parameters must have to change until the bearing capacity for the foundation is higher than load from structure.

9.2 Average Settlement and Differential Settlement

The average settlement and differential settlement should be lesser than the maximum allowable settlement. Usually, in the design requirement, there will be stated the maximum settlement that can acceptable in the design. So, it is a must to make sure that the calculated average settlement and differential settlement less than allowable settlement. Different type of structures can have different design requirement for allowable settlement

2.2.1 Settlement of friction piles in clay

When friction piles are used under a raft to support them, the settlements of the piles are substantially reduced since the loads are transferred from the raft to the greater depth of subsoil. Friction piles are different from end-bearing piles where the load are transfer over the entire surface area of the pile .This is because the friction piles are not installed or driven until reach the hard layer. Whereas in end-bearing pile, the load is transmitted through the pile and transfer it to the hard layer.

The settlement can be reduced more as the length of the piles becomes longer. In settlement of friction piles, the settlement in predicted on the assumption that the net load from the structure is transferred to a depth to two – thirds the pile length and that dispersion of the load takes places into soil from this level. See Figure 9.1

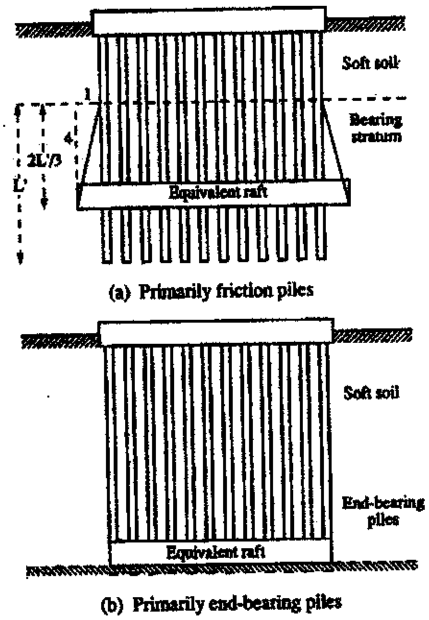


Figure 9.1: Transfer of load for settlement for friction piles and end-bearing piles

9.2.2 Differential settlement control

In order to achieve an ideal piled raft as differential controller, the required pile that required may be estimated by consideration of the 'ideal' contact pressure distribution that acts beneath a rigid raft.

At the central of raft, the contact pressure is approximately half of the average applied pressure. Therefore, the number and the length of piles at the center should be higher than other part of the raft. Thus, it will give minimal differential settlement

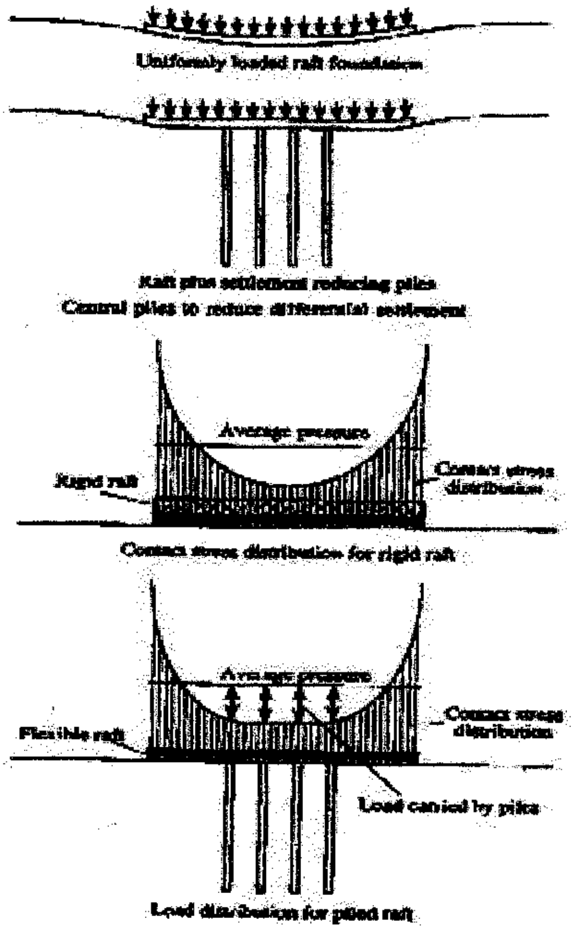


Figure 9.2: Differential control of piled raft

REFERENCES

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5. Craig, R. F. 2004, *Craig's Soil Mechanics,* Spon Press

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Table 5.1: Laboratory Test Schedule

BOREHOLE	SAMPLE NO.	DEPTH m	M/C	A.L.	B.D.	S.G.	VOID RATIO	SIEVE ANALYSIS		CONSOLIDATION			TRIAXIAL		UCT	CHEMICAL ANALYSIS			
								Mech.	Hydro.	Std.	Rapid	S.S.	CIU	UU		ORGANIC CONTENT	PH	SULPHATE CONTENT	CHLORIDE CONTENT
BH-14	U3-1	1.5 - 2.5		X				X	X	X								X	X
	D2	4.5 - 4.95		X				X	X										
	U3-2	8.5 - 9.5		X				X	X				X			X	X		
	D8	14.0 - 14.45		X				X	X										
	D11	[illegible]		X				X	X										
	D14	[illegible]		X				X	X										
BH-17	[illegible]	[illegible]		X				X	X										
	M2	[illegible]		X				X	X				X						
	[illegible]	[illegible] - 13.95		X				X	X										
	D10	18.0 - 18.36		X				X	X										
	D13	22.5 - 22.8		X				X	X										
TOTAL	Requested		-	11	-	-	-	11	11	1	-	-	2	-	-	1	1	1	1
	Performed																		

Note :

1) CIU - Isotropic Consolidated Undrained Triaxial Test with pore pressure measurements
- Use 70mm diameter sample (i.e. untrimmed Mazier sample)
- Sample should not have side filter during consolidation
- Shearing strain should be calculated using C_v values calculated during consolidation stage.
- Multi-stage testing not allowed
- P-Q Stress Path Plotting shall be submitted.

2) For CIU Tests, stress path and other relevant data shall be submitted in Hard Copy (Plots and Tabulated Data) and Soft Copy (Computer files data). Cell confining pressure of 0.5 σ_v, 1.0σ_v, 2.0σ_v shall be adopted for the CIU test, where σ_v is the total vertical in-situ stress.

3) UU - Unconsolidated Undrained Test (at total overburden pressure of the sample)

4) UCT - Unconfined Compression Test (untrimmed sample)

5) To determine Cv from Consolidation Tests :-
- Use Square-Root Time Method to determine d_0
- Then use Log-Time Method to determine d_{50}

6) Direct shear box test - Three (3) reconstituted specimens (60mm x 60mm x 20mm thick) shall be used.
- Applied normal stress pressure of 0.5 σ_v, 1.0σ_v, 2.0σ_v shall be adopted for the CIU test, where σ_v is the total vertical in-situ stress.

Appendix A

Table 5.3: British Soil Classification System for Engineering Purposes

Soil Groups			Subgroup and laboratory identification			
GRAVEL and SAND may be qualified sandy GRAVEL and gravelly SAND, etc.,where appropriate			Group symbol	Subgroup symbol	Fines (% less than 0.06mm)	Liquid limit
COARSE SOILS Less than 35% of the material is finer than 0.06mm	GRAVELS More than 50% of coarse material is of gravel size (coarser than 2mm)	Slightly silty or clayey GRAVEL	GW G GP	GW GPu GPg	0 to 5	
		Silty GRAVEL Clayey GRAVEL	G-M G-F GC	GWM GPM GWC GPC	5 to 15	
		Very silty GRAVEL Very clayey GRAVEL	GM GF GC	GML, etc GCL GCI GCH GCV GCE	15 to 35	
	SANDS More than 50% of coarse material is of sand size (finer than 2mm)	Slightly silty or clayey SAND	SW S SP	SW SPu SPg	0 to 5	
		Silty SAND Clayey SAND	S-M S-F S-C	SWM SPM SWC SPC	5 to 15	
		Very silty SAND Very clayey SAND	SM SF SC	SML, etc SCL SCI SCH SCV SCE	15 to 35	
FINE SOILS More than 35% of the material is finer than 0.006mm	Gravelly or sandy SILTS and CLAYS 35% to 65% fines	Gravelly SILT Gravelly CLAY	MG FG CG	MLG, etc CLG CIG CHG CEG		<35 35 to 50 50 to 70 70 to 90 90 >
		Sandy SILT Sandy CLAY	MS FS CS	MLS, etc CLS, etc		
	SILTS AND CLAYS 65% to 100% fines	SILT (M –SOIL) CLAY	M F C	ML, etc CL CI CH CV CE		<35 35 to 50 50 to 70 70 to 90 90 >
ORGANIC SOILS		Descriptive letter 'O' suffixed to any group or subgroup symbol				
PEAT		Pt				

Working PileTest 2 on MP-3(Pilecap 2a-Na)

Load (% of WL)	Holding Time (min)	Load (kN)	Dial Gauge Readings: Gauge 'A'	Gauge 'B'	Gauge 'C'	Gauge 'D'	Average	Pile Settlement (mm)	Optical Readings: Rider 'T' (Jack)	Pile Head Settlement - Jack (mm)	Difference of Pile Settlement (Dial Gauge / Optical)	% of Difference	Rider 'Z' (on RB)	Rider 'X' (on RB)	Rider 'Y' (TBM)	Additional steel used from pile head: Rider 'S' (from pile head)	Pile Head Settlement (Optical) (mm)
0.0	0	0	50	50	50	50	50.000	0.000	160	0.0	0.000	0	150.0	100	135	150	0.0
12.5	15	26	49.73	49.77	49.75	49.77	49.755	0.245	160	0.0	0.245	100	150.0	100	135	150	0.0
		26	49.74	49.77	49.75	49.78	49.760	0.240	160	0.0	0.240	100	150.0	100	135	150	0.0
25.0	15	53	49.5	49.59	49.55	49.57	49.553	0.448	160	0.0	0.448	100	150.0	100	135	150	0.0
		53	49.54	49.59	49.55	49.57	49.563	0.438	160	0.0	0.438	100	150.0	100	135	150	0.0
37.5	15	79	49.38	49.42	49.37	49.39	49.390	0.610	160	0.0	0.610	100	150.0	100	135	150	0.0
		79	49.38	49.42	49.37	49.39	49.390	0.610	160	0.0	0.610	100	150.0	100	135	150	0.0
50.0	15	105	49.2	49.25	49.2	49.21	49.215	0.785	160	0.0	0.785	100	150.0	100	135	150	0.0
		105	49.2	49.25	49.2	49.21	49.215	0.785	160.5	0.5	0.285	36	150.0	100	135	150	0.0
62.5	15	131	48.95	49.01	48.94	48.95	48.965	1.035	161	1.0	0.035	3	150.0	100	135	150.5	0.5
		131	48.95	49.01	48.94	48.96	48.955	1.035	161	1.0	0.035	3	150.0	100	135	150.5	0.5
75.0	15	158	48.82	48.80	48.81	48.83	48.835	1.165	161	1.0	0.165	4	150.0	100	135	150.5	0.5
		158	48.84	48.89	48.82	48.85	48.848	1.153	161	1.0	0.153	13	150.0	100	125	150.5	0.5
87.5	15	184	48.41	48.45	48.4	48.42	48.423	1.578	161	1.0	0.578	37	150.0	100	135	151	1.0
		184	48.42	48.46	48.4	48.42	48.425	1.575	161	1.0	0.575	37	150.0	100	135	151	1.0
100.0	60	210	48.15	48.19	48.14	48.14	48.155	1.845	161.5	1.5	0.345	19	150.0	100	135	151	1.0
		210	48.17	48.21	48.14	48.17	48.173	1.828	161.5	1.5	0.328	18	150.0	100	135	151	1.0
		210	48.11	48.16	48.1	48.1	48.118	1.883	161.5	1.5	0.383	22	150.0	100	135	151	1.0
		210	48.1	48.14	48.1	48.1	48.110	1.890	161.5	1.5	0.390	21	150.0	100	135	151	1.0
		210	48.1	48.14	48.1	48.1	48.110	1.890	161.5	1.5	0.390	21	150.0	100	135	151	1.0
75.0	15	158	48.25	48.3	48.25	48.28	48.273	1.728	161	1.0	0.727	42	150.0	100	135	151	1.0
		158	48.27	48.3	48.25	48.29	48.278	1.723	161	1.0	0.723	42	150.0	100	135	151	1.0
50.0	15	105	48.65	48.68	48.64	48.68	48.663	1.338	161	1.0	0.337	25	150.0	100	135	150.5	0.5
		105	48.66	48.7	48.65	48.68	48.678	1.323	161	1.0	0.323	24	150.0	100	135	150.5	0.5
25.0	15	53	49.42	49.46	49.44	49.45	49.445	0.555	160	0.0	0.555	100	150.0	100	135	150	0.0
		53	49.43	49.47	49.45	49.48	49.458	0.542	160	0.0	0.542	100	150.0	100	135	150	0.0
0.0	15	0	49.75	49.77	49.77	49.8	49.773	0.227	160	0.0	0.227	100	150.0	100	135	150	0.0
		0	49.77	49.76	49.78	49.81	49.785	0.215	160	0.0	0.215	100	150.0	100	135	150	0.0
50.0	15	105	49.05	49.09	49.06	49.02	49.063	0.938	160	0.0	0.938	100	150.0	100	135	150	0.0
		105	49.02	49.09	49.06	49.07	49.060	0.940	160	0.0	0.940	100	150.0	100	135	150	0.0
100.0	15	210	48.0	48.05	48.02	48.0	48.018	1.983	161	1.0	0.983	50	150.0	100	135	151	1.0
		210	48.0	48.05	48.02	48.0	48.018	1.983	161	1.0	0.983	50	150.0	100	135	151	1.0
125.0	15	263	47.5	47.55	47.5	47.49	47.510	2.490	162	2.0	0.490	20	150.0	100	135	151.5	1.5
		263	47.5	47.55	47.5	47.49	47.510	2.490	162	2.0	0.490	20	150.0	100	135	151.5	1.5
150.0	15	315	46.72	46.76	46.71	46.69	46.720	3.280	163	3.0	0.280	9	150.0	100	135	152	2.0
		315	46.79	46.83	46.77	46.76	46.785	3.215	163	3.0	0.215	7	150.0	100	135	152	2.0
175.0	15	368	45.85	45.9	45.81	45.79	45.838	4.163	164	4.0	0.163	4	150.0	100	135	153	3.0
		366	45.94	45.97	45.88	45.88	45.918	4.083	164	4.0	0.083	2	150.0	100	135	153	3.0
200.0	60	420	44.94	44.97	44.88	44.84	44.91	5.093	165	5.0	0.093	1.82	150.0	100	135	154	4.0
		420	44.99	44.99	44.90	44.88	44.94	5.060	165	5.0	0.060	1.19	150.0	100	135	154	4.0
		420	45.01	45.02	44.94	44.9	44.97	5.032	165	5.0	0.032	0.65	150.0	100	135	154	4.0
		420	45.01	45.02	44.94	44.9	44.97	5.033	165	5.0	0.032	0.65	150.0	100	135	154	4.0
		420	45.01	45.02	44.94	44.9	44.97	5.033	165	5.0	0.032	0.65	150.0	100	135	154	4.0
150	15	315	45.99	45.9	45.81	45.81	45.85	4.150	164	4.0	0.150	3.61	150.0	100	135	153	3.0
		315	45.9	45.91	45.81	45.81	45.86	4.143	164	4.0	0.142	3.44	150.0	100	135	153	3.0
100	15	210	46.93	46.98	46.9	46.9	46.93	3.073	163	3.0	0.072	2.36	150.0	100	135	152	2.0
		210	46.93	46.98	46.9	46.9	46.93	3.073	163	3.0	0.072	2.36	150.0	100	135	152	2.0
50	15	105	48.33	48.38	48.35	48.35	48.35	1.653	161	1.0	0.653	39.45	150.0	100	135	151	1.0
		105	48.55	48.58	48.57	48.58	48.57	1.430	161	1.0	0.430	30.07	150.0	100	135	151	1.0
0	15	0	49.41	49.42	49.43	49.45	49.43	0.573	160	0.0	0.573	100	150.0	100	135	150	0.0
		0	49.45	49.45	49.45	49.47	49.46	0.545	160	0.0	0.545	100	150.0	100	135	150	0.0

Table 1: Example of datasheet from Pile Load test

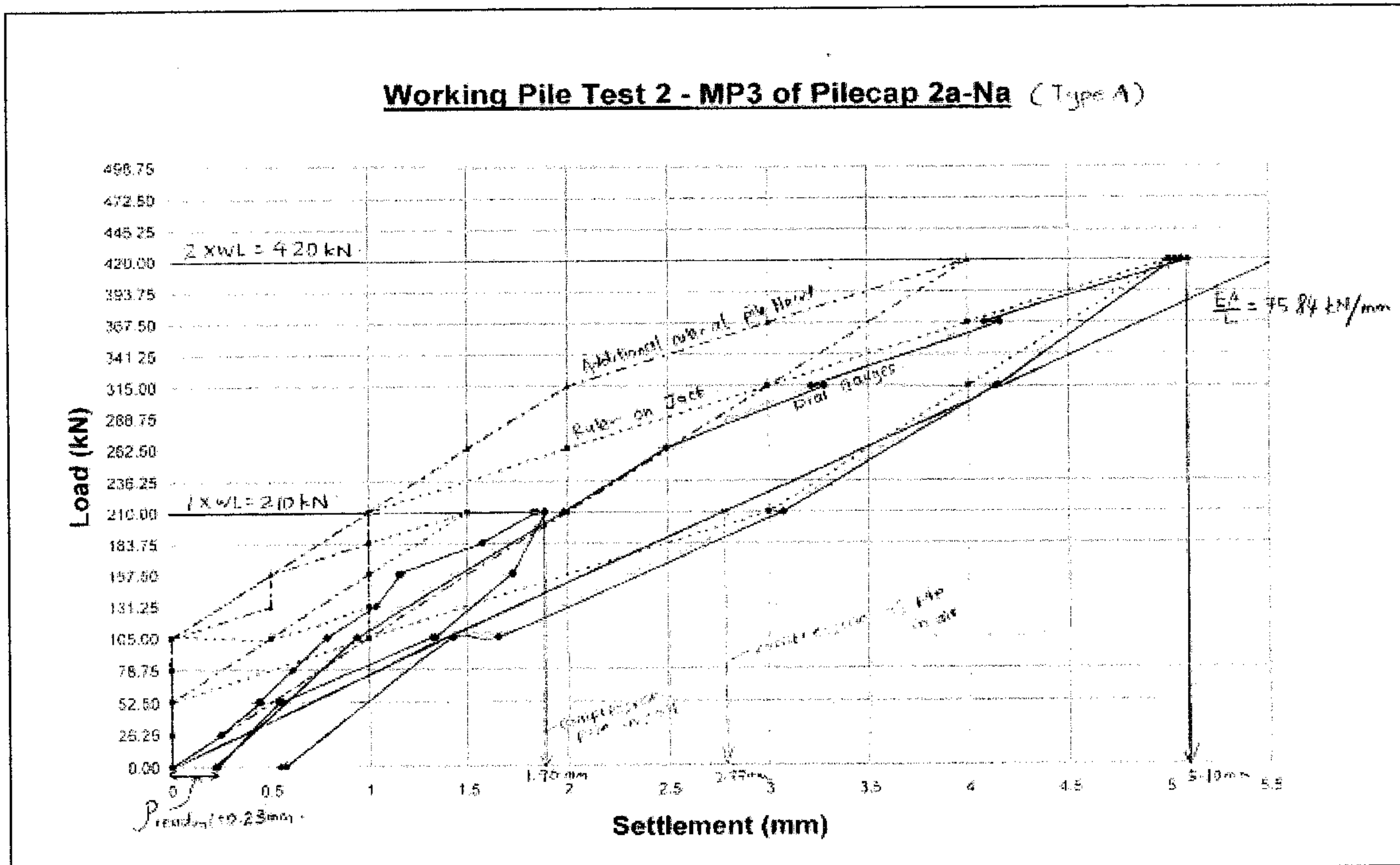


Figure 1: Graph of Load vs Settlement from Pile Load test

Appendix B

Worked Example 7.1

Determination of Elastic Young's Modulus of Pile from Pile Load Test

Diameter of micropile = 200mm

Length = 15m

$$E_{steel} = 205\frac{kN}{mm^2}$$

$$= 2.05 \times 10^8 kN/m^2$$

$$A_{steel} = 3 \times \frac{\pi}{4}(20)^2$$

$$= 942.48\ mm^2\ or\ 9.425\ \times 10^{-4} m^2$$

$$E_{grout} = 31\ 000MPa\ (for\ grout\ confined\ in\ acased\ length)$$

$$= 3.1 \times 10^7 kN/m^2$$

$$A_{grout} = \frac{\pi}{4}(200)^2 - 942.48mm^2$$

$$= 30\ 473.45\ mm^2$$

$$= 3.047\ \times 10^{-2} m^2$$

$$A_{composite} = \frac{\pi}{4}(200)^2$$

$$= 31\ 416\ mm^2$$

$$= 3.142\ \times 10^{-2} m^2$$

Appendix B

$$E_{composite}A_{composite} = \left(E_{grout} \cdot A_{grout}\right) + \left(E_{steel} \cdot A_{steel}\right)$$

$$E_{composite}$$

$$= \frac{(3.1 \times 10^{7} kN/m^{2} \times 3.047 \ \times 10^{-2} m^{2}) + (2.05 \times 10^{8} kN/m^{2} \times 9.425 \ \times 10^{-4} m^{2})}{3.142 \ \times 10^{-2} m^{2}}$$

$$= 36\ 212\ 046.47\ kN/m^{2}$$

$$= 3.621 \times \frac{10^{7} kN}{m^{2}}$$

$$= 36\ 212\ kN/mm^{2}$$

Appendix B

WORKED EXAMPLE 8.1

In order to illustrate the design calculation discussed in the guideline, a simple example will be analyzed. For this example, the piles distribution will be uniformly distributed, whereas in design practiced, piles distribution will based on load from the column. The column that have higher load will have more piles and maybe longer that others. The applied load will assume uniformly distributed also.

Below are the parameters given for the design of the foundation:
Uniformly distributed applied load: 3.5 MN

Raft parameters		Pile parameters		Soil parameters	
E_r	35 000 MPa	Ep	35 000MPa	G_s	100 MPa (Table 6.2)
L	3 m	Lp	15 m	E_s	150 MPa (Table 6.1)
B	3 m	Size	150mm x 150mm (RC square pile)	v_s	0.4 (Table 6.4)
t_r	0.6 m				
v_r	0.3				

Design Calculation:
Applied load = **3.5 MN**

i) Number of piled and spacing

q_u of clay = 126kN/m^2 (based on Table 6.4, assumed clay is stiff)
Factor of safety = 3

Allowable load per pile
- Surface area of piles

= d_p x no.of pile surface x L_p (Square pile = no of surface = 4)
= 0.15m x 4 x 15m
=9 m^2

- Allowable skin resistance

$= \frac{q_u}{2} \times \frac{\alpha}{FS}$

$= \frac{126kN/m^2}{2} \times \frac{0.75}{3}$ (α is based on Figure 8.1)

= $15.75kN/m^2$

Allowable load per pile (Eq. 8.3)
= $15.75kN/m^2 \times 9$ m^2
= **141.75kN**

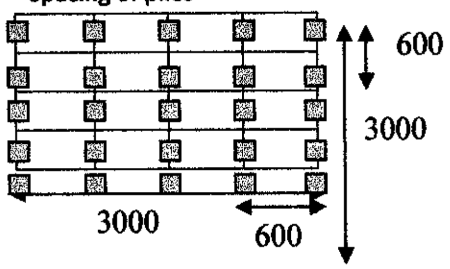
Appendix B

Thus, number of piles required (Eq.8.4)

$$= \frac{(3.5 \times 1000)kN}{141.75kN}$$

$= 24.69 \approx$ **25 piles**

Spacing of piles



Minimum spacing = 3d

= 3 x 150mm = 450 mm < **600mm** (acceptable)

ii) Piled raft bearing capacity

Safe bearing capacity (Eq. 8.7)

$$= \frac{q_u N_c}{6} \times \left[1 + 0.2\frac{B}{L}\right]$$

$$= \frac{126kN/m^2 (5.14)}{6} \left[1 + 0.2\frac{3}{3}\right]$$

= 129.53 kN/m^2

Bearing capacity of raft (Eq. 8.8)

= 129.53 kN/m^2 x (3m x 3m)

= 1 165.77 kN

Allowable surface shear (Eq. 8.10)

$$= \frac{q_u}{6} \text{ x surface area}$$

$$= \frac{126 \text{ kN/m2}}{6} \times [(2(3m)(15m)) + (2(3m)(15m))]$$

= 3 780kN

Appendix B

Thus, piled raft bearing capacity (Eq. 8.11)

= 1 165.77 kN + 2 772 kN

= **4 945.77 kN** > 3 500 kN , O. K

iii) Raft stiffness

Average stiffness of raft (Eq. 8.13)

$= [G_s/(1-\upsilon_s)]\beta_z(4cd)^{\frac{1}{2}}$

$$= \left[\frac{100}{1-0.4}\right]2.15(4(1.5)(1.5))^{\frac{1}{2}}$$

= **1 075 MN/m**

iv) Pile group stiffness

- Single pile stiffness (Eq. 8.14)

$$\frac{P_t}{G_l r_o w_t} = \frac{\left[\frac{4}{1-\nu_s}\right]+\left\{\left(\frac{2\pi\rho}{\zeta}\right)\left(\frac{\tanh(\mu l)}{\mu l}\right)\left(\frac{L_P}{r_o}\right)\right\}}{1+\left\{\left(\frac{4}{\pi\lambda(1-\nu_s)}\right)\left(\frac{\tanh(\mu l)}{\mu l}\right)\left(\frac{L_P}{r_o}\right)\right\}}$$

d_p = 150mm

r_o= 150mm/2 =75 mm=0.075m

G_l = 100 MN/m^2

$\rho = G_{ave}/G_l$ =100 MN/m^2/ 100 MN/m^2

ρ = 1

$$r_m = 2.5\rho(1-\upsilon_s)L_p$$

= 2.5(1)(1-0.4)(15)

= **22.5**

$$\zeta = \ln(r_m/r_o)$$

= ln (22.5/0.075)

= **5.70**

$$\lambda = \left(\frac{E_p}{G_l}\right)$$

$$= \frac{35\,000}{100} = 350$$

$$\mu l = \sqrt{\left(\frac{2}{\zeta\lambda}\right)}\left(\frac{L_p}{r_o}\right)$$

$$= \sqrt{\left(\frac{2}{(5.70)(350)}\right)}\left(\frac{15}{0.075}\right)$$

= **6.33**

Single pile stiffness:

$$\frac{P_t}{w_t} = \frac{\left[\frac{4}{1-0.4}\right]+\left\{\left(\frac{2\pi(1)}{5.70}\right)\left(\frac{\tanh(6.33)}{6.33}\right)\left(\frac{15}{0.075}\right)\right\}}{1+\left\{\left(\frac{4}{\pi(350)(1-0.4)}\right)\left(\frac{\tanh(6.33)}{6.33}\right)\left(\frac{15}{0.075}\right)\right\}} \times (100 \times 0.075)$$

= **261.197 MN/m**

- **Pile group effieciency**

Pile group efficiency, η_w (Eq. 8.15)

$$= n^{-e}$$

Base value for *e*, refer upper part of Figure 8.2, slenderness ratio L/d = 15m/0.15m = 100

So, base value of efficiency exponent, *e* = 0.51

Then, refer to bottom part of Figure 8.2 to obtain 4 exponent correction factors based on:

i) Stiffness ratio, E_p/G_l = 350 , $\log_{10}$ 350 = 2.5
   e correction factor = 0.875

ii) Spacing ratio, s/d = 4
   e correction factor = 0.93

iii) Poisson ratio, nu = 0.4
   e correction factor = 0.975

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iv) Homogeneity factor, $\rho = 1$

e correction factor = 1.06

Corrected efficiency exponent, e = 0.51 x (0.875x0.93x0.975x1.06)

= 0.4289

Pile group efficiency, $\eta_w = 25^{-0.4289}$

= 0.2514

Thus, pile group stiffness (Eq. 8.16)

$k_p = \eta_w nk_1$

= 0.2514 (25) (261.197 MN/m)

$= \mathbf{1\ 641.84}\ \boldsymbol{MN/m}$

v) Piled raft stiffness

Area of raft = $n\pi r_r^2$

$9m^2 = 25\pi\, r_r^2$

$r_r = 0.339$ m

α_{rp} = interaction factor

$$= \frac{In\,(\frac{r_m}{r_r})}{In(\frac{r_m}{r_o})}$$

$$= \frac{In\,(\frac{22.5}{0.339})}{In(\frac{22.5}{0.075})}$$

= **0.735**

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Thus, piled raft stiffness (Eq. 8.17)

$$= \frac{[k_p + k_r(1-2\alpha_{rp})]}{\left[1-\alpha_{rp}^2\left(\frac{k_r}{k_p}\right)\right]}$$

$$= \frac{[1\ 641.84\ \mathrm{MN/m} + 1\ 075\ \mathrm{MN/m}(1-2(0.735))]}{\left[1-(0.735)^2\left(\frac{1\ 075\ \mathrm{MN/m}}{1\ 641.84\ \mathrm{MN/m}}\right)\right]}$$

= 1 746.597MN/m

vi) Average settlement (Eq. 8.19)

$$= \frac{applied\ vertical\ load}{piled\ raft\ stiffness}$$

$$= \frac{3.5\ MN}{1\ 734.82\ MN/m}$$

= 2.004 mm

vii) Differential settlement

Raft-soil stiffness, k_{rs} (Eq.8.20)

$$k_{rs} = 5.57\left(\frac{E_r}{E_s}\right)\left[\frac{(1-v_s^2)}{(1-v_r^2)}\right]\left(\frac{B}{L}\right)^{0.5}\left(\frac{t_r}{L}\right)^3$$

$$= 5.57\left(\frac{35\ 000}{150}\right)\left[\frac{(1-0.4^2)}{(1-0.3^2)}\right]\left(\frac{3}{3}\right)^{0.5}\left(\frac{0.6}{3}\right)^3$$

= 9.6

From Figure 8.3, normalized differential settlement, Δw = 0.025 (mid-side), Δw = 0.042 (corner)

Thus, average differential settlement (Eq.8.21)

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- Mid-side to centre

= Δw x Average settlement

= 0.025 x 2.004mm

= 0.0501mm (unfactored)

= 0.051mm x $\frac{1\,641.84\ \text{MN/m}}{1746.597\text{MN/m}}$ (Eq. 8.22)

= 0.0467 mm (factored value)

- Corner to center

= 0.042 x 2.02mm

= 0.0842mm (unfactored)

= 0.0848 mm x $\frac{1\,641.84\ \text{MN/m}}{1746.597\text{MN/m}}$

= 0.0785mm (factored value)

viii) Load distribution between raft and pile group

The proportion load carried by raft and piles can be calculated using Eq. 8.23

$$\frac{P_r}{(P_r + P_p)} = \frac{[k_r(1-\alpha_{rp})]}{[k_p + k_r(1-2\alpha_{rp})]}$$

$$= \frac{[1\,075\ \text{MN/m}(1-0.735\ )]}{[1\,641.84\,MN/m + 1\,075\ \text{MN/m}(1-2(0.735)\ )]}$$

= 0.25 (Raft)

Load carried by piles = 1 – 0.25 = 0.75 or 75%

Load carried by raft = 0.25 or 25%

Due to the load portion carried by piles is 75% , the number of piles assumed in the early step can be reduced from 25 to maybe 23. This because, in the early calculation, we assumed the piles carried 100% of the total load. But, as reminder, load portion by raft and piles can be done theoretically but in construction perspectives, it needs a crucial construction.