PERFORMANCE OF FLOATING PILED RAFT WITH VARYING LENGTHS IN SOFT COMPRESSIBLE SUBSOIL

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To my beloved parents and family

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ABSTRACT

Conventional piled foundation usually provides adequate load carrying capacity to limit the settlement within allowable limits. However, in deep layer of soft compressible subsoil with settling platform, this foundation system faces numerous problems namely requiring very long piles, lower pile capacity due to downdrag forces, and hollow gap formed beneath the slab of piled structures when the earth platform settled causing services to break and poses health hazard. This research proposed an analysis and design methodology for an alternative foundation system of 'floating' piled raft (FPR) with same or varying pile lengths to resolve the problems stated above. The design objectives are to control differential settlement, angular distortion and bending moment rather than only limiting total settlement. The proposed analysis and design methodology bridges the research gaps of using piled raft in soft compressible subsoil. This incorporate long term settlement in the analysis to cater for piles of varying lengths and can be used by practicing engineers for design works. Parametric studies were carried out to verify the proposed analysis and design methodology through modelling of 'floating' piled raft with different numbers of piles, lengths configurations, spacing of piles and also different raft thickness. The vertically loaded pile rafts analysed are 3x3, 6x6 and 9x9 number of piles respectively with total combination of 108 cases that cover different pile lengths of same and varying lengths, different pile spacing and different raft thickness. The research findings showed that piled raft with combination of varying pile lengths is generally more effective in reducing differential settlement, ratio of ($\Delta\rho/\rho_{max}$), bending moment of the raft and angular distortion (β) compared to pile raft with similar pile length (even with longest piles). The findings from the parametric studies contributed to a better understanding on the performance and behaviour of 'floating' piled raft in soft compressible subsoil especially on the piled raft of varying piled lengths. The proposed analysis and design methodology in this research has also been successfully used to design 'floating' piled raft foundation system in deep and soft compressible subsoil to support low rise buildings of 2-storey to 5-storey that have been constructed and occupied for more than 10 years. This confirmed the benefits obtained from this research to have a realiable and efficient analysis and design methodology through better understanding of the performance and behaviour of 'floating' piled raft foundation with same or varying pile lengths.

ABSTRAK

Asas cerucuk konvensional biasanya mempunyai keupayaan menanggung beban untuk menghadkan enapan pada had yang dibenarkan. Walaubagaimanapun, di dalam lapisan lembut yang dalam dengan pelantar yang mengenap, sistem asas ini menghadapi pelbagai masalah seperti memerlukan cerucuk yang panjang. Keupayaan cerucuk yang rendah akibat daya seret ke bawah dan ruang kosong terbentuk di bawah papak disokong oleh cerucuk apabila pelantar tanah mengenap menyebabkan laluan perkhidmatan pecah dan mengancam kesihatan. Hasil kajian mencadangkan analisis dan metodologi rekabentuk untuk sistem asas alternatif menggunakan asas rakit bercerucuk 'terapung' (FPR) samada dengan panjang cerucuk yang sama atau panjang cerucuk yang pelbagai bagi menyelesaikan masalah ini. Objektif rekabentuk adalah untuk mengawal perbezaan enapan, sudut herotan dan momen lentur berbanding hanya menghadkan jumlah enapan. Analisis dan metodologi rekabentuk ini menjadi hubungan bagi jurang dalam kajian penggunaan asas rakit bercerucuk dalam lapisan tanah lembut boleh mampat. Ini menggabungkan enapan jangka masa panjang di dalam analisis, mengambilkira cerucuk dengan panjang yang pelbagai dan boleh digunakan pengamal jurutera dalam kerja rekabentuk. Kajian parametrik bagi mengesahkan analisis dan rekabentuk ini melalui permodelan asas rakit cerucuk 'terapung' dengan bilangan cerucuk, konfigurasi panjang, jarak antara cerucuk dan ketebalan rakit yang berbeza-beza telah di laksanakan. Asas rakit bercerucuk dengan beban pugak yang dianalisis adalah 3x3, 6x6 dan 9x9 bilangan cerucuk dengan 108 jumlah kombinasi kes; merangkumi panjang cerucuk yang berbeza-beza samada dengan panjang cerucuk yang pelbagai atau sama, jarak antara cerucuk yang berbeza dan ketebalan rakit yang berbeza. Penemuan kajian menunjukkan asas rakit bercerucuk dengan kombinasi panjang cerucuk yang pelbagai secara amnya lebih efektif dalam mengurangkan bezaan enapan, nisbah ($\Delta\rho/\rho_{max}$), momen lentur rakit dan sudut herotan (β) berbanding dengan rakit bercerucuk yang mempunyai panjang cerucuk yang sama walaupun dengan cerucuk yang paling panjang. Penemuan daripada kajian parametrik ini menyumbang kepada pemahaman lebih jelas tentang prestasi dan sifat rakit bercerucuk 'terapung' dalam tanah lembut terutamanya untuk rakit bercerucuk dengan pelbagai panjang. Cadangan analisis dan metodologi rekabentuk di dalam kajian ini telah digunakan dengan jayanya untuk merekabentuk sistem asas rakit bercerucuk dalam lapisan tanah lembut dan dalam bagi menampung beban bangunan setinggi 2 hingga 5 tingkat yang telah dibina dan diduduki lebih daripada 10 tahun. Ini telah mengesahkan manfaat yang diperolehi hasil daripada kajian ini iaitu untuk menambah baik metodologi analisis dan rekabentuk yang boleh dipercayai dan efisyen melalui pemahaman terhadap prestasi serta sifat asas rakit bercerucuk 'terapung' dengan sama panjang atau pelbagai.

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LIST OF SYMBOLS

ω_s	-	Pile displacement
τ_0	-	Shear stress
r_0	-	Radius of the pile
G	-	Soil shear modulus
r_m	-	Maximum radius of influence of the pile
ρ	-	Measure of the vertical homogeneity
$\eta = r_b / r_0$	-	Ratio of under-ream for under-reamed piles
$\xi = G_l / G_b$	-	Ratio of end-bearing for end-bearing piles
$\rho = G_{ave} / G_l$	-	Variation of soil modulus with depth
$\lambda = E_p / G_l$	-	Pile-soil stiffness ratio
$\zeta = \ln(r_m / r_0)$	-	Measure of radius of influence of pile
$\mu L_p = \sqrt{(2/\zeta\lambda)}(L_p / r_0)$	-	Measure of pile compressibility
I	-	Obtained from the product of a number of other Coefficients which reflects features
q	-	Average pressure applied to the raft
I_ε	-	An influence factor of vertical strain
h_i	-	Thickness of i[th] layer of subsoil
E_i	-	Young's moduls of i[th] layer of subsoil
F_D	-	Correction factor from Fox (1948)
d_{eq}	-	Diameter of equivalent pier (m)
A_g	-	Plan area of the piled raft (m^2)
E_{eq}	-	Young's modulus of equivalent pier (kN/m^2)
E_S	-	Young's modulus of subsoil (kN/m^2)
E_p	-	Young's modulus of piles (kN/m^2)

A_{tp}	-	Total cross-sectional area of the piles in the group (m^2)
A_g	-	Plan area of the piled raft (m^2)
R	-	If smaller than 4, equivalent pier method is suitable. It is even better if the value is less than 2
n	-	Number of piles
s	-	Pile spacing (m)
L_p	-	Pile length (m)
w_i	-	Settlement of pile *i* within a group of *n* piles
P_{av}	-	Average load on a pile within the group
S_1	-	Settlement of a single pile under unit load (i.e., the pile flexibility)
α_{ij}	-	Interaction factor for pile *i* due to other pile (*j*) within the group.
S_{1e}	-	Elastic flexibility of the pile
R_f	-	Hyperbolic factor (taken as unity)
P	-	Load on pile *i*
P_u	-	Ultimate load capacity of pile *i*
q	-	Analysis exponent
	-	2 for incremental non-linear analysis
	-	1 for equivalent linear analysis
s	-	Centre to centre spacing between pile *i* and *j*
ρ	-	Ratio of soil modulus at mid-length of pile to that at the level of the pile tip (1 for constant modulus and 0.5 for "Gibson" soil which has Young's modulus linearly increasing with depth)
γ	-	$\ln(2r_m/d)$
Γ	-	$\ln(2r_{m2}/ds)$
r_m	-	$2.5(1-\upsilon)\rho L$
L	-	Pile length
d	-	Pile diameter

Λ	-	L/d
k_1 *to* k_4	-	Fitting parameters
E_{sL}	-	Soil modulus at mid-length of the pile
E_b	-	Modulus of bearing stratum below ile tip
r_g	-	A group distance defined by Randolph & Wroth (1979)
w	-	Vertical deflection
r_m	-	Limiting radius of influence of the pile
l	-	Pile length
ν	-	Poisson ratio of the soil
P_b	-	Load acting on the pile base
c	-	$2/\pi$
$G_{l/2}$	-	Shear modulus of soil at pile mid-depth
G_l	-	Shear modulus of soil at pile base
P_s	-	Load acting on the pile shaft
α_v	-	Interaction factor
$(\mu l)^2$	-	$(2/\zeta\lambda)(l/r_0)^2$
λ	-	E_p/G_l
A_p	-	Cross Section Area of the Pile
σ'_0	-	In-situ effective vertical stress
σ'_c	-	Pre-consolidation Pressure /Yield Stress
CR	-	Compression ratio = $\dfrac{C_c}{1+e_0}$
RR	-	Recompression ratio = $\dfrac{C_r}{1+e_0}$
C_c	-	Compression Index
C_r	-	Recompression Index
H_i	-	Initial thickness of incremental soil layer, *i* of *n* layers
σ_0	-	Foundation contact pressure
I_q	-	Factor of intensity of pressure

L	-	Length of area loaded
B	-	Width of area loaded
Z	-	Depth of soil layer of interest
m	-	L/B
n	-	z/B
$K_{pile-total,q,i=0}$	-	Stiffness of pile support (unit in kN/m)
$P_{pile,q,i=0}$	-	Axial point load acting pile (unit in kN)
$\delta_{pile-total,q,i=0}$	-	Total combined settlement of the pile raft at each pile point location (unit in m)
q	-	Pile point reference number
I	-	Iteration number
$K_{soil-total,r,i=0}$	-	Stiffness of soil support beneath each section of raft (unit in kPa/m)
$p_{raft,r,i=0}$	-	Uniform load acting on each section of raft (unit in kPa)
$\delta_{raft-total,r,i=0}$	-	Total combined settlement of the pile raft at the midpoint of each section of raft (unit in m)
r	-	Reference number for each section of raft
E	-	Young modulus of soil. $E \approx 200s_u$ to $400s_u$ for soft clay
N_q	-	$e^{\pi\tan\phi'}\tan^2(45+\phi'/2)$
N_c	-	$(N_q-1)\cot\phi'$
N_γ	-	$(N_q-1)\tan(1.4\phi')$
s_c	-	$1 + 0.2K_p(B/L)$; for any ϕ'
$s_q = s_\gamma$	-	$1 + 0.1K_p(B/L)$; for $\phi'>10^o$
$s_q = s_\gamma$	-	1 ; for $\phi'=0^o$
α	-	Adhesion factor
s_u	-	Undrained shear strength (in kPa)
N_c	-	Bearing capacity factor = 9
Q_{ag}	-	Allowable geotechnical capacity
Q_{su}	-	Ultimate shaft capacity = $\sum_i (f_{su} \times A_S)$
i	-	Number of soil layers

Q_{bu}	-	Ultimate base capacity = f_{bu} A_b
f_s	-	Unit shaft resistance for each layer of embedded soil
f_b	-	Unit base resistance for the bearing layer of soil
A_s	-	Pile shaft area
A_b	-	Pile base area
F_s	-	Partial Factor of Safety for Shaft Resistance of 'floating' pile as settlement reducer = 1.1 to 1.2
F_b	-	Partial Factor of Safety for Base Resistance of 'floating' pile as settlement reducer = 1.5 to 2.0
F_g	-	Global Factor of Safety for Total Resistance of 'floating' pile as settlement reducer = 1.2 to 1.5
α_{pr}	-	Pile raft coefficient
$\sum R_{piles}$	-	Sum of piles resistance
R_{total}	-	Total imposed load

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Conventional piled foundation, commonly designed and constructed in Malaysia, is usually designed for buildings/structures to provide adequate load carrying capacity, to limit the overall settlement and hence indirectly control differential settlement to within tolerable limits. Piles are often installed into competent stratum or to ‘set’ (terminate) in hard layer. Therefore to date, design methods commonly used by practicing engineers in Malaysia still concentrate on providing adequate axial capacity from the piles to carry all the structural loads without detailed evaluation of pile settlement. Usually, the estimation of settlement is considered as a secondary issue and sometimes ignored because of the nature of load transfer between pile and soil, particularly where shaft resistance provides a major component of the total pile capacity which will automatically lead to small acceptable settlement. However, this conventional design methodology faces numerous problems over the years when adopted in deep layer of soft compressible subsoil of alluvial and marine deposits. This type of geological formation is commonly found in majority of the areas along the coast of Peninsular Malaysia and also East Malaysia namely the infamous clay at Klang, Muar and Sibu. Neighbouring countries such as Thailand, Indonesia and Singapore also have similar alluvial or marine deposits.

As the country develops, good competent ground (e.g. hard residual soils) are becoming scarce and development especially for housing (especially for low and medium cost houses and flats) and also for industrial usage (e.g. tanks farm, factory and plants) have to be constructed in the low lying or swampy areas with deep soft compressible subsoil. In these areas, hard competent stratum is sometime as deep as 40m to 60m therefore making conventional method requiring long slender piles. To make things worse, at these low lying areas (sometimes water logged) the earthworks platform for the buildings has to be raised by earth filling above the flood level. The weight of the earth fill on top of the soft compressible subsoil induces both primary and secondary consolidation settlement with time.

The conventional piled to 'set' design methodology only addresses the short-term problem associated with soft clay as the allowable pile capacity (allowable load to be imposed on the piles from the building) will be significantly reduced because the allowable geotechnical capacity has to be downgraded to cater for negative skin friction (down drag) induced by the settling soft compressible subsoil. This often reduces the cost-effectiveness of such 'conventional solution' as the pile capacity (both allowable geotechnical and structural capacity) has to be downgraded (reduced) thus requiring more piles or larger pile sizes for same loading compared to piles that are not experiencing down drag. Other than being uneconomical, conventional method of piled to 'set' also causes long term serviceability problems such as large abrupt differential settlement between the piled buildings/structures and the surrounding earth platform on compressible subsoil that is still undergoing settlement with time. The abrupt differential settlement with large enough magnitude causes problem such as breakages of water and sewerage pipes. The hollow gap formed beneath the building, due to larger settlement of the earth platform compared to the buildings supported by piles installed into competent stratum, becomes a health and safety hazard to the public as mosquitoes, rats, snakes and other animals can make this area their habitat as shown in Figure 1.1.

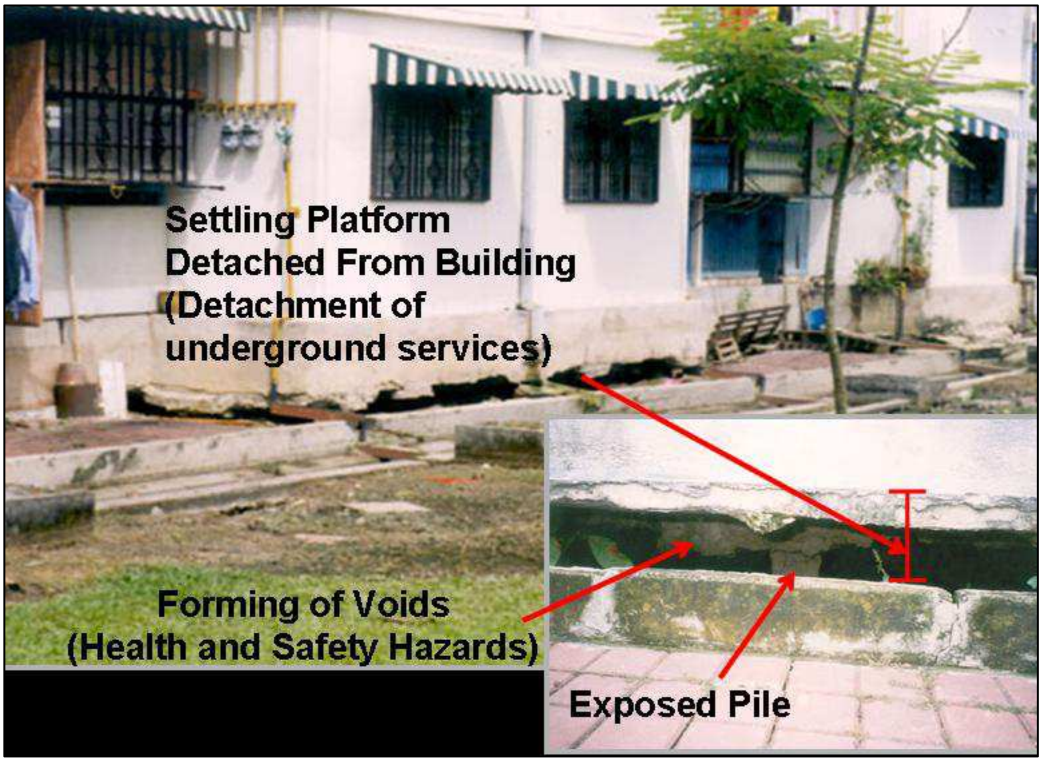

Figure 1.1 Problems for buildings with piled to 'set' foundation on soft ground

1.2 Problem Statement

Being aware of all the problems associated with conventional method of piled to 'set' in deep layer of soft compressible subsoil, it is important to propose an alternative foundation method of 'floating' piled raft (FPR) foundation system that would eliminate all the problems stated above. In summary, the proposed foundation method shall be economical, technically suitable, safe and satisfy both ultimate and serviceability limit states of the buildings to be supported. This foundation system would benefit the construction industry in particular and the development of the country as a whole. However, in order to achieve this, the proposed foundation system shall have practical analysis and design methodology that practicing engineers in Malaysia would find it user friendly and not too difficult so that it can be widely used to carry out day-to-day analysis and design.

Therefore, when developing the analysis and design methodology for the proposed foundation system, it is necessary to make some practical simplifications and realistic assumptions, but the proposed methodology shall not lose the correctness of the proposed method that can be calibrated by actual site measurements of the buildings constructed and performance of the actual buildings such as no architectural, structural or services damage. This is like carrying out very costly full-scale actual test to prove the usefullness and appropriateness of the proposed analysis and design methodology. Many researches may not have this luxury and opportunity as it would be very costly and time consuming. Fortunately, this is possible for this research as the researcher through his consulting firm was involved in the actual projects in Malaysia and Indonesia that adopted the researcher’s proposed analysis and design methodology.

1.3 Research Objectives

Although extensive research in piled raft has been carried out and published as presented in literature review, however, the following issues have not been fully addressed which will form the research objectives:-

i. To look into the possibility and suitability of using ‘floating’ piled raft (FPR) foundation system in soft compressible subsoil for low rise buildings.

ii. To develop an analysis and design methodology for an alternative foundation system of ‘floating’ piled raft foundation system of same or varying pile lengths that take into consideration of the long term settlement of the subsoil. The proposed analysis and design methodology should be able to be used by practicing engineers for day to day design works.

iii. To solve long term serviceability problems of conventional piled to set foundation system in soft compressible subsoil by allowing ‘floating’ piled raft to settle together with the platform.

iv. To understand the performance and behaviour of ‘floating’ piled raft in soft compressible subsoil especially on the piled raft with combination of varying piled lengths.

1.4 Scope of Works

The scope of works for this research are as follows:-

i. For vertically loaded piled raft in soft compressible subsoil only.

ii. Proposed analysis and design methodology can cater for piles of varying sizes, lengths and loads.

iii. The piles shall be ‘floating’ piles which means the piles are not installed into hard stratum.

iv. Terzaghi’s consolidation theory is used for the evaluation of the magnitude of consolidation settlement.

v. For parametric studies, the vertically loaded piled rafts analysed are 3x3, 6x6 and 9x9 number of piles respectively with total combination of 108 cases that cover different pile lengths, different pile spacing and different raft thickness.

vi. Case studies on two completed projects designed using the proposed methodology and constructed:-

a) 2-storey terrace houses at Bandar Botanic , Klang

b) 5-storey medium rise apartment at Bandar Botanic, Klang

1.5 Significant of Study

This research was carried out to focus on the development of analysis and design methodology for the proposed alternative foundation system of ‘floating’ piled raft (FPR) foundation system of same or varying pile lengths. The design objectives are to control differential settlement, angular distortion and bending moment rather than only limiting total settlement. The estimations of differential settlement and angular distortion are the most critical issues in the design of large sized pile raft which the raft behaves as flexible raft, these movements are the main culprits causing a building to crack and lose its function and even collapse. Piles of varying lengths can be provided under the raft in order to limit settlements (both total and differential) to an acceptable level thus achieving the required angular distortion.

Based on the analysis and design methodology developed in this research, parametric studies were carried out to model the ‘floating’ pile raft (FPR) of different numbers of piles, lengths configurations, spacing of piles and also different raft thickness. The results obtained from these modelling will be presented and discussed in detailed to show the application of the proposed analysis and design methodology. The results also provide a better understanding on the performance and behaviour of ‘floating’ piled raft in soft compressible subsoil especially on the effectiveness of piled raft with combination of varying piled lengths to control differential settlement, angular distortion and bending moment. Finally, the analysis and design methodology developed can be used by practicing engineers for day to day design of piled raft in soft compressible subsoil which will help the development of the engineering practice in Malaysia.

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