COMPARISON BETWEEN METHODS OF ANALYSIS FOR DEFLECTION OF LATERALLY LOADED PILES

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Especially to my Father, Low Kheng Kin, Mother, Yong Hee Hung,
Grandfather, Kapitan Lau Nguong Tieng
And
My beloved late grandmother, Ling Ai Ting.
You guide me to success.

ACKNOWLEDGEMENT

Special thank to my supervisor, Professor Dr. Khairul Anuar Kassim for his guidance, assistance and encouragement in all aspects of this Master Project. His positive comments and remedies during the course of preparing this project are gratefully acknowledged. His continuous patience and availability to attend to any doubts whenever needed deserves my heartiest gratitude.

I wish to express my sincere appreciation to my colleagues for their encouragement, guidance, and assistance. Without their continued support and interest, this project report would not have been the same as presented here.

I would also like to take this opportunity to thank my fellow postgraduate course mates in the Faculty of Civil Engineering for their continuous support, discussions and friendly interactions during the course of my study. Their friendship always keeps me going to achieve my dreams. My heartiest appreciation also goes to all academic and non-academic members of the Faculty of Civil Engineering, for their continuous cooperation during the duration of my study in Universiti Teknologi Malaysia.

Great appreciation is expressed to my father, Low Kheng Kin and my mother, Yong Hee Hung. Without their understanding, support and encouragement in assisting me to pursue my Masters Degree, I may not have come thus far.

ABSTRACT

Deep foundation, which used extensively to support highway structures, machinery foundation, high rise building, etc are often subjected to both axial and lateral loads. To obtain a safe and economical design, the method adopted for design of lateral deflection must be appropriate. In this thesis, two different methods of analysis for the ground-line deflection of the single, elastic, free-head piles have been compared with the available test results obtained from full-scale instrumented test piles. The basis for comparison is on the variation in pile installation methods and types of soil in Malaysia. Two design methods were selected; one is the rational method of Broms and the other is a more rigorous method of Characteristic Load Method (CLM). From the results obtained, it is found that Broms' method gives more conservative value (around 59% to 70% larger than measured value) of lateral deflection compared to CLM. Lateral deflections calculated using CLM were found to be in good agreement (around 2% to 24% larger than measured value) with values measured in field load tests.

ABSTRAK

Asas dalam yang mana digunakan dengan banyak untuk menanggung struktur lebuhraya, asas bagi tapak mesin-mesin, bangunan cakar langit, dan lain-lain selalu tertakluk kepada beban terus dan sisi untuk mendapatkan satu rekabentuk yang selamat dan ekonomik, kaedah rekabentuk pesongan sisi yang digunapakai mesti berpatutan. Dalam tesis ini, dua kaedah mudah digunakan untuk menganalisa dan membandingkan pesongan pada permukaan tanah bagi cerucuk individu, cerucuk elastic dan cerucuk *free-head* yang diperolehi daripada keputusan ujian yang dijalankan ke atas cerucuk yang diistrumentasikan. Asas bagi perbandingan ini adalah berdasarkan kepada perbezaan dalam kaedah pemasangan dan jenis tanah di Malaysia. Dua kaedah rekabentuk dipilih; Kaedah Broms yang rasional dan Kaedah Beban Karateristik (CLM). Kaedah Broms memberikan nilai pesongan sisi yang lebih konservatif (lebih kurang 59% hingga 70% lebih besar dari nilai yang diukur) berbanding dengan CLM. Pengiraan pesongan sisi menggunakan kaedah CLM pula menunjukkan nilai yang hampir (lebih kurang 2% hingga 24% lebih besar dari nilai yang diukur) dengan nilai yang dihitung daripada ujian beban tapak.

TABLE OF CONTENTS

1 INTRODUCTION

2 LITERATURE REVIEW

CHAPTER **TITLE** **PAGE**

CHAPTER **TITLE** **PAGE**

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a_1, a_2	Constant for Load-deflection and Moment-deflection
b_1, b_2	Exponent for Load-deflection and Moment-deflection
c_u	Undrained shear strength
$C_{p\phi}$	Passive pressure factor
D, d	Diameter
e	Height of the pile from the point of application of the load to the ground surface
E_p	Elastic modulus of the pile
f_{cu}	Grade of concrete
H	Horizontal force or applied lateral load
$I_{circular}$	Moment of inertia of a solid circular cross section
I_p	Moment of inertia of the pile
k, k_1	Coefficient of subgrade reaction
k_∞	Coefficient of subgrade reaction
K_p	Rankine Coefficient of Passive Resistance
K_0	Coefficient of subgrade reaction
L	Total pile length from pile cut-off level
m_1, m_2	Constant for Characteristic Load and Moment
M_c	Characteristic Moment
M_p	Equivalent moment
M_t	Moment
n_h	Coefficient of modulus variation
n_1	Coefficient of compressive strength of the soil
n_2	Coefficient of material forming the pile
P_c	Characteristic Load
P_m	Equivalent load

P_t	Applied lateral load
r_1, r_2	Exponent for Characteristic Load and Moment
R_I	Moment of inertia ratio
s_u	Undrained shear strength
y, y_t	Ground-line deflection
y_{comb}	Average ground-line deflection
y_{tm}	Ground-line deflection due to applied moment
y_{tp}	Ground-line deflection due to applied load
y_{tmp}	Ground-line deflection due to applied moment plus equivalent moment
y_{tpm}	Ground-line deflection due to applied load plus equivalent load
$\propto$	Factor
β	Coefficient of pile length
ε_{50}	Axial strain at 50% of the soil strength
ϕ'	Effective friction angle
γ	Unit weight of soil
γ_b	Bulk unit weight of soil
γ_w	Unit weight of water
η	Coefficient of pile length
λ_1, λ_2	Dimensionless parameter for Characteristic Load and Moment
σ_p	Passive pressure of the soil

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Thesis

Most structures are subject to lateral loads as a result of wind, earthquake, impact, waves, and lateral earth pressure. If these structures are supported on deep foundations, the foundations have to be designed to cater for lateral loads. Thus, such foundations should be designed to satisfy three conditions: (1) the pile should be able to carry the imposed load with an adequate margin of safety against failure in bending; (2) The deflection for the foundation under load should not be larger than the tolerable deflection for the structure it supports; and (3) The soil around the pile should not be loaded so heavily that it reaches its ultimate load-carrying capacity.

In most cases considerations of bending moments and deflection govern the design, because the ultimate load carrying capacity of the soil is reached only at very large deflections. The ultimate capacity of the soil around the pile may not be fully mobilised, however, its response is nonlinear. As a result, the relationship among load, moment, and deflection for laterally loaded deep foundations are nonlinear. It is therefore important to base design of laterally loaded piles on methods of analysis that model the nonlinear behaviour of the soil-foundation system.

In recent years, extensive theoretical approaches for predicting lateral deflection or moment have been developed. For example, the subgrade reaction approach by Barber (1953) and Matlock and Reese (1960), the *p*-*y* curve method by

Reese (1977), finite-element method by Bowles (1988) which assumes the soil to be as in the Winkler model and the elastic continuum approach by Poulos and Davis (1980), Duncan, Evans and Ooi (1994), Zhang and Small (2000), and Shen and Teh (2002). These aforementioned methods, however, need complex computer programs to perform fully numerical analysis and this makes them less accessible to practicing engineers in the routine design.

1.2 Nature of the problem

The application of a lateral load to the top of a pile will result in the lateral deflection of the pile. The reactions that are generated in the soil should be such that the equations of static equilibrium are satisfied, and the reactions should be consistent with the deflections. Also because no pile is completely rigid, the amount of pile bending must be consistent with the soil reactions and the pile stiffness.

Thus, the problem of the laterally loaded pile is a “soil-structure-interaction” problem. The solution of the problem requires that numerical relationships between pile deflection and soil reaction be known and that these relationships be considered in obtaining the deflected shape of the pile.

The problem seems formidable; however, two technological advances have allowed the problem to be solved with relative ease. Instrumentation that enables strains to be read remotely has made possible the determination of soil response during the testing of full-scale piles. And computer allows the deflected shape of a pile to be computed rapidly and accurately even though the soil reaction against the pile is a nonlinear function of pile deflection and depth below the ground surface.

1.3 Influence of Analytical Method on Engineering Practice

Some engineering practices employ the rational method for design of piles under lateral loading. No formal survey have been made, but informal conversations with a number of engineers indicate that one or more of the following approximate methods are currently in use: (1) assignment of a nominal lateral load for vertical piles as recommended in building codes; (2) use of raked piles where the horizontal component of the axial load balances the horizontal forces; and (3) making computations with the Broms' method. The use of the rational method should lead to improvement in designs. However, for some major projects, load tests to ascertain lateral capacities are advisable.

If the rational method is used to get the response of a pile, structural engineers will have sufficient information to design the pile foundation to sustain the required loads. Combined stresses can easily be computed and reinforcement can be employed at proper positions along a pile. The reinforcement for combined stresses can consist of additional reinforcing steel or perhaps an increased diameter in some instances. If a portion of the pile extends above the ground level, the computer solution can be employed to investigate the possibility of buckling.

The approximate methods probably lead, in almost all instances, to an overdesign with regard to lateral loading. This overdesign results in increased cost. If there is an underdesign of a pile that is subjected to lateral loading, the result will be excessive deflection or a complete collapse of the system.

Thus, five common methods are available for the solution of a single pile under lateral load. These are: elastic method, curves and charts, static method (Broms' method), computer method (nonlinear soil response), and dimensionless curves.

1.4 Aim and Objective of the Thesis

The aim of this thesis is to provide a simple and easy method to analysis the ground-line deflection for

i) Single piles,
ii) Long elastic pile, which the embedded pile length is more than four (4) times of stiffness factor of pile and soil, and
iii) Free-head or unrestrained piles, which free rotation occurs at the head.

In order to achieve the aim of the thesis, three objectives have been identified:

i) To compare the obtained theoretical results with the field test results.
ii) To compare the results based on pile installation methods in cohesionless soil.
iii) To compare the results based on types of soil for cast in-situ bored piles.

Therefore, two simple methods of analysis namely Broms' method and Characteristic Load Method (CLM) have been selected to analyse the ground-line deflection to achieve the aims and objectives of the thesis. The calculated results will be compared with the available test data obtained from full-scale instrumented test piles in Malaysia.

1.5 Scope

The instrumented full-scale static load test were carried out for three various sites from West Coast of Peninsular Malaysia. The locations for the selected sites of the study are as shown in Figure 1.1.

Figure 1.1: Location of Test Piles Site

Since the soil near the top of pile is most important with regard to response to the lateral load, the point of reference to classify the type of soil is terminated at the depth of fixity for lateral deflection which is 1.8 times of pile stiffness factor or 8 diameters of the piles below ground surface. All piles and soil parameters obtained from the test field were used in design analyses of Broms' method and CLM. The lateral deflections at ground-line were calculated based on the type of pile and soil for comparison purposes.

1.6 Important of Thesis

The comparison between the selected design methods with measured data from instrumented full-scale static load test for deflection of laterally loaded piles could assist geotechnical engineer in adopting a more appropriate method in design of piles under lateral loading.

In Malaysia, many engineering practices employ the rational method of Broms or using sophisticated computer software for designing and analyse the laterally loaded piles. The results obtained from this thesis will provide geotechnical engineers an option of selecting a simple, quick and easy examine solution.