

**COMPARISON BETWEEN METHODS OF  
ANALYSIS FOR DEFLECTION OF  
LATERALLY LOADED PILES**

**LOW SIAW MEI**

**UNIVERSITI TEKNOLOGI MALAYSIA**

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 diinstrumentasikan. 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 Karakteristik (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

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xii
	<b>LIST OF FIGURES</b>	xiv
	<b>LIST OF SYMBOLS</b>	xvi
	<b>LIST OF APPENDICES</b>	xviii
<b>1</b>	<b>INTRODUCTION</b>	
	1.1 Background of Thesis	1
	1.2 Nature of the Problem	2
	1.3 Influence of Analytical Method on Engineering Practice	3
	1.4 Aim and Objective of the Thesis	4
	1.5 Scope	4
	1.6 Important of Thesis	6
<b>2</b>	<b>LITERATURE REVIEW</b>	
	2.1 Background	7
	2.2 Broms' Method	8
	2.2.1 Introduction	9

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	2.2.2 Concepts Employed in Broms' Method	9
	2.2.3 Broms' Deflection Equations	10
	2.2.3.1 Piles in Cohesionless Soil	10
	2.2.3.2 Piles in Cohesive Soil	10
2.3	Characteristic Load Method	11
	2.3.1 Introduction	11
	2.3.2 Concepts of Characteristic Load Method	12
	2.3.3 Characteristic Load Method Equations	13
	2.3.3.1 Dimensionless Relationship with Characteristic Load $P_c$ and Moment $M_c$	13
	2.3.3.2 Deflection due to Combined Load and Moment	15
<b>3</b>	<b>INSTRUMENTED FIELD LOAD TEST</b>	
	3.1 Introduction	17
	3.2 Selection of Test Pile	18
	3.3 Installation of Test Pile	18
	3.4 Testing Procedures	19
	3.5 Interpretation of Data	21
<b>4</b>	<b>METHODOLOGY</b>	
	4.1 Introduction	22
	4.2 Data Collection	23
	4.3 Data Analysis	24
	4.3.1 Calculating Ground-Line Deflection using Method of Broms	24
	4.3.2 Calculating Ground-Line Deflection using Characteristic Load Method	25
	4.4 Data Presentation	25
	4.5 Data Interpretation and Results	26

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
<b>5</b>	<b>DATA COLLECTION</b>	
	5.1 Introduction	27
	5.2 Site 1 – 1400MW Coal Fired Power Plant Project in Jimah, Negeri Sembilan	28
	5.2.1 Introduction	28
	5.2.2 Geological Background of the Site	29
	5.2.3 Appreciation of Subsoil Condition after Reclamation	30
	5.2.4 Scope	30
	5.2.5 Location of the Test Piles and Subsurface Information	31
	5.2.6 Test Piles Installation	32
	5.2.6.1 1050mm Diameter Cast In-situ Bored Piles Installation	32
	5.2.6.2 600mm Diameter Spun Bored Installation	33
	5.2.7 Proposed Instrumentation	33
	5.2.8 Pile Movement Monitoring System	34
	5.2.9 Static Maintained Load Test	34
	5.2.10 Test Results	35
	5.2.10.1 Test Results for 1050mm Diameter Cast In-situ Bored Piles	35
	5.2.10.2 Test Results for 600mm Diameter Spun Piles	39
	5.3 Site 2 – 2100MW Coal Fired Power Plant Project in Tanjung Bin, Johor	43
	5.3.1 Introduction	43
	5.3.2 Geological Background of the Site	43
	5.3.3 Appreciation of Subsoil Condition after Reclamation	44
	5.3.4 Scope	45



<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	5.3.5 Location of the Test Piles and Subsurface Information	45
	5.3.6 Test Piles Installation	45
	5.3.7 Proposed Instrumentation	46
	5.3.8 Pile Movement Monitoring System	46
	5.3.9 Static Maintained Load Test	47
	5.3.10 Test Results	48
5.4	Site 3 – A-380 Hangar/Workshop Facility at MAS Complex in KLIA, Sepang, Selangor	51
	5.4.1 Introduction	51
	5.4.2 Geological Background of the Site	51
	5.4.3 Scope	52
	5.4.4 Location of the Test Piles and Subsurface Information	53
	5.4.5 Test Piles Installation	53
	5.4.6 Proposed Instrumentation	54
	5.4.7 Pile Movement Monitoring System	54
	5.4.8 Static Maintained Load Test	55
	5.4.9 Test Results	56
<b>6</b>	<b>DATA ANALYSIS</b>	
	6.1 Introduction	61
	6.2 Ground-Line Deflection Formulations	62
	6.2.1 Broms' Ground-Line Deflection Formulation	63
	6.2.2 CLM's Ground-Line Deflection Formulation	66
<b>7</b>	<b>RESULTS AND DISCUSSIONS</b>	
	7.1 Introduction	73
	7.2 Results of Analyses for Ground-Line Deflection	73

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	7.3 Comparison with Pile Installation Methods in Cohesionless Soil	76
	7.4 Comparison with Types of Soil for Cast In-situ Bored Piles	78
	7.5 Investigation of the Case for Spun Piles Installed in Cohesionless Soil	80
	7.6 Discussion	83
	7.7 Summary of Results and Discussion	83
<b>8</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b>	
	8.1 Conclusions	85
	8.2 Recommendations	86
	<b>REFERENCES</b>	87
	<b>APPENDICES</b>	89-129

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Values of coefficient $n_1$ (after Broms, 1964a)	11
2.2	Values of coefficient $n_2$ (after Broms, 1964a)	11
2.3	Minimum Pile Lengths for Characteristic Load Method	12
2.4	Typical $\varepsilon_{50}$ values (Matlock, 1970)	14
2.5	Values of the exponents $m$ and $n$ (Evans and Duncan, 1982)	14
2.6	Constants for Load-deflection equations $y_t / D = a_1(P_t / P_c)^{b1}$ (Brettmann & Duncan, 1996)	15
2.7	Constants for Moment-deflection equations $y_t / D = a_2(M_t / M_c)^{b2}$ (Brettmann & Duncan, 1996)	15
5.1	Summary of Site Data	28
5.2	Summary of Subsoil Information for Site 1	31
5.3	Summary of Pile Information for 1050mm Diameter Cast In-situ Bored Piles at Site 1	32
5.4	Summary of Pile Information for 600mm Diameter Spun Piles at Site 1	33
5.5	Summary of the Lateral Deflection for 1050mm Diameter Cast In-situ Bored Piles at Site 1	36
5.6	Summary of the Lateral Deflection for 600mm Diameter Spun Piles at Site 1	40
5.7	Summary of Subsoil Information for Site 2	45
5.8	Summary of Pile Information for 600mm Diameter Spun Piles at Site 2	46

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
5.9	Summary of the Lateral Deflection for 600mm Diameter Spun Piles at Site 2	49
5.10	Summary of Subsoil Information for Site 3	53
5.11	Summary of Pile Information for 1050mm Diameter Cast In-situ Bored Piles at Site 3	54
5.12	Summary of the Lateral Deflection for 1050mm Diameter Cast In-situ Bored Piles at Site 3	57
7.1	Summary of the Lateral Deflection for 600mm Diameter Spun Piles in Cohesionless Soil	74
7.2	Summary of the Lateral Deflection for 1050mm Diameter Cast In-situ Piles in Cohesionless Soil	75
7.3	Summary of the Lateral Deflection for 1050mm Diameter Cast In-situ Piles in Cohesive Soil	76
7.4	Summary of the Lateral Deflection for 600mm Diameter Spun Piles in Cohesionless Soil at Site 1, Jimah, Negeri Sembilan	80
7.5	Summary of the Lateral Deflection for 600mm Diameter Spun Piles in Cohesionless Soil at Site 2, Tanjung Bin, Johor	80

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Location of Test Piles Site	5
2.1	Long Vertical Free-head Pile under Horizontal Load	7
3.1	Typical Set-up for Simultaneous Testing of Two Piles under Lateral Loading	20
3.2	Device for Measuring Pile-Head Displacement	21
4.1	Sequence Used to Carry Out the Comparison of the Calculated and Measured Lateral Deflection of the Test Piles	23
5.1	Typical Subsoil Profile (Borehole ref. ABH-27)	29
5.2	Plot of Lateral Deflection for TP1 at Site 1 from LVDTs and Inclinator Measurements	38
5.3	Plot of Lateral Deflection for TP2 at Site 1 from LVDTs and Inclinator Measurements	38
5.4	Plot of Lateral Deflection for TP3c at Site 1 from LVDTs and Inclinator Measurements	42
5.5	Plot of Lateral Deflection for TP4 at Site 1 from LVDTs and Inclinator Measurements	42
5.6	Typical Subsoil Profile (Borehole ref. BBH-12)	44
5.7	Plot of Lateral Deflection for TP2a at Site 2 from LDT and Inclinator Measurements	50
5.8	Plot of Lateral Deflection for TP2b at Site 2 from LDT Measurements	50
5.9	Typical Subsoil Profile (Borehole ref. BH-6)	52

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
5.10	Plot of Lateral Deflection for TP1 at Site 3 from LSDTs and Inclinometer Measurements	60
5.11	Plot of Lateral Deflection for TP2 at Site 3 from LSDTs and Inclinometer Measurements	60
6.1a	Spreadsheet of Broms' Ground-Line Deflection Formulation (Part 1 of 2)	63
6.1b	Spreadsheet of Broms' Ground-Line Deflection Formulation (Part 2 of 2)	64
6.2a	Spreadsheet of CLM's Ground-Line Deflection Formulation (Part 1 of 2)	66
6.2b	Spreadsheet of CLM's Ground-Line Deflection Formulation (Part 2 of 2)	67
7.1	Comparison of Measured and Calculated Lateral Deflections for Driven Piles	77
7.2	Comparison of Measured and Calculated Lateral Deflections for Cast In-situ Bored Piles	77
7.3	Comparison of Measured and Calculated Lateral Deflections for Cast In-situ Bored Piles in Cohesionless soil	79
7.4	Comparison of Measured and Calculated Lateral Deflections for Cast In-situ Bored Piles in Cohesive soil	79
7.5	Comparison of Measured and Calculated Lateral Deflections for 600mm Diameter Spun Piles in Site 1, Jimah, Negeri Sembilan	81
7.6	Comparison of Measured and Calculated Lateral Deflections for 600mm Diameter Spun Piles in Site 2, Tanjung Bin, Johor	81
A.1	Location Plan for the Test Piles No. TP1, TP2, TP3c and TP4	90
A.2	Set-Up/Arrangement and Instrumentation Plan for TP1 and TP2	101

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
A.3	Plan View on Set-Up/Arrangement and Instrumentation for TP1 and TP2	102
A.4	Set-Up/Arrangement and Instrumentation Plan for TP3c and TP4	109
B.1	Location Plan for the Test Piles No. TP2a and TP2b	112
B.2	Set-Up/Arrangement and Instrumentation Plan for TP2a and TP2b	119
B.3	Set-Up/Arrangement and Instrumentation Plan for TP2a and TP2b	120
C.1	Location Plan for the Test Piles No. TP1 and TP2	122
C.2	Set-Up/Arrangement and Instrumentation Plan for TP1 and TP2	128

## 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
$k_\infty$	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
$\alpha$	Factor
$\beta$	Coefficient of pile length
$\varepsilon_{50}$	Axial strain at 50% of the soil strength
$\phi'$	Effective friction angle
$\gamma$	Unit weight of soil
$\gamma_b$	Bulk unit weight of soil
$\gamma_w$	Unit weight of water
$\eta$	Coefficient of pile length
$\lambda_1, \lambda_2$	Dimensionless parameter for Characteristic Load and Moment
$\sigma_p$	Passive pressure of the soil

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Test Pile Details for 1050mm Diameter Cast In-situ Bored Piles (TP1 and TP2) and 600mm Diameter Spun Piles (TP3c and TP4)	86
A.1	1050mm Diameter Cast In- situ Bored Piles	88
A.2	600mm Diameter Spun Piles	101
B	Test Pile Details for 600mm Diameter Spun Piles (TP2a and TP2b)	108
C	Test Pile Details for 1050mm Diameter Cast In-situ Bored Piles (TP1 and TP2)	118

## 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.