

**THE EFFECT OF LIMITED SITE INVESTIGATIONS
ON THE DESIGN AND PERFORMANCE
OF PILE FOUNDATIONS**

Ardy Arsyad

THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF ENGINEERING SCIENCE

in

The University of Adelaide
(School of Civil, Environmental and Mining Engineering)

July 2008

*To my wife Dian Andini, my sons Alif Ardian Arsyad and
Muhammad Terzaghi Ramadhan,
and my parents Muhammad Arsyad Kadiro and Yusniar Yusuf*

Preface

The work described in this thesis was undertaken over the period of 2 years, between July 2006 and July 2008, within School of Civil, Environmental, and Mining Engineering at the University of Adelaide. Throughout the thesis, all materials, techniques, concepts and conclusions obtained from other sources have been acknowledged in the text.

Abstract

The research presented in this thesis focuses on the quantification of the effect of limited site investigations on the design and performance of pile foundations. Limited site investigation is one of the main causes of structural foundation failures. Over the last 30 years, most site investigations conducted for infrastructure projects have been dictated by minimum cost and time of completion, rather than meeting the need to appropriately characterise soil properties (Institution of Civil Engineers 1991; Jaksa et al. 2003). As a result, limited site investigations remain common, resulting in a higher risk of structural foundation failure, unforeseen additional construction, and/or repair costs. Also, limited site investigations can result in over-designing foundations, leading to increased and unnecessary cost (ASFE 1996).

Based on the reliability examination method for site investigations introduced by Jaksa et al. (2003) and performed by Goldsworthy (2006), this research investigated the effect of limited site investigations on the design of pile foundations. This was achieved by generating three-dimensional random fields to obtain a virtual site consisting of soil properties at certain levels of variability, and by simulating various numbers of cone penetration tests (CPTs) and pile foundations on the generated site. Once the site and the CPTs were simulated, the cone tip resistance (q_c) was profiled along the vertical and horizontal axes.

The simulated q_c profiles yielded by the CPTs were then used to compute axial pile load capacity termed the pile foundation design based on site investigations (SI). In parallel, the axial pile load capacity of the simulated pile foundation utilising the “true” cone tip resistance along the simulated pile was also determined. This is termed “the true” design, or the benchmark pile foundation design, and referred to as pile foundation design based on complete knowledge (CK). At the end of this process, the research compared the pile foundation designs based on SI and those based on CK. The reliability of the foundation design based on SI was analysed with a probabilistic approach, using the Monte Carlo technique.

The results indicated that limited site investigations have a significant impact on the design of pile foundations. The results showed that minimum sampling efforts result in a high risk of over- or under-designing piles. More intensive sampling efforts, in contrast, led to a low risk of under- or over-design. The results also indicated that the levels of spatial variability of the soil are notable factors that affect the effectiveness of site investigations. These results will assist geotechnical engineers in planning a site investigation in a more rational manner with knowledge of the associated risks.

Statement of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying.

Signed : Date:.....

Acknowledgments

This M.Eng.Sc, research began in July 2006 and was completed in July 2008. I owe an enormous debt to my supervisors, Assoc. Prof. Mark Jaksa, and Dr. William Kaggwa, of the School of Civil, Environmental, and Mining Engineering, for their time, patience, guidance and continual support throughout this research program. In addition, their endless encouragement and constant assistance have been of great value to me, and this thesis would not have been possible but for their contribution. I also express my respect and gratitude to Professor Gordon Fenton of Dalhousie University Canada for his very useful modules for simulating 3-dimensional soil variability; Dr. Jason Goldsworthy for sharing his extensive experience in developing simulation modules, Dr. Stephen Carr of the School of Civil, Environmental, and Mining Engineering for his valuable advice and computing facilities, and to the Faculty of Engineering, Computer and Mathematical Sciences for providing access to the supercomputer *Hydra*.

I wish to thank fellow postgraduate students: Yien Lik Kuo, Brendan Scott, Ibrisam Akbar, Yun Hang Chok, Su Yu, Matthew Haskett, Tim Rowan, Jakin Ravalico, Mathew Gibbs, and Fernando Gayani, for their friendship, encouragement and advice. In addition, thanks are also due to Niranjala Seimon of the International Student Centre for her assistance during my candidature, and Mrs. Barbara Brougham of the Centre of Learning and Professional Development (CLPD) for her assistance with this thesis.

I would also like to thank the Government of Australia for financial support given to me during my candidature through the Australian Partnership Scholarship (APS) scheme.

I will always be indebted to my family, particularly my wife, Dian, and my sons, Alif and Terzaghi, for their constant love, sacrifice and support throughout the period of my candidature, and my father, Arsyad who passed away during my candidature, and my mother, Yusniar, for the considerable sacrifices which they

have made for me throughout my life. Finally, I am indebted to Allah Subhanahu Wata'ala for the strength, nourishment and opportunities which I have been blessed with during this period of study.

Contents

<i>Preface</i>	<i>i</i>
<i>Abstract</i>	<i>ii</i>
Statement of Originality.....	<i>iv</i>
<i>Acknowledgements</i>	<i>v</i>
<i>Contents</i>	<i>vii</i>
<i>List of Figures</i>	<i>x</i>
<i>List of Tables</i>	<i>xiii</i>
<i>Notation</i>	<i>xiv</i>
Chapter 1. Introduction	1
1.1 THE CONTEXT OF THE STUDY	1
1.2 THE NATURE OF THE PROBLEM	1
1.3 STATEMENT OF THE RESEARCH PROBLEM	3
1.4 METHODOLOGY	3
1.5 ORGANISATION OF THE THESIS	4
Chapter 2. Literature Review	5
2.1 INTRODUCTION	5
2.2 CHARACTERISATION OF GROUND CONDITIONS	5
2.2.1 The Cone Penetration Test (CPT).....	8
2.2.2 Standard Penetration Test (SPT).....	10
2.2.3 Mappings and Samplings	12
2.3 PILE FOUNDATION DESIGN	14
2.3.1 Pile Load Capacity	14
2.3.2 LCPC Method.....	19
2.4 UNCERTAINTY IN GEOTECHNICAL ENGINEERING	22
2.4.1 Soil Variability	22
2.4.2 Statistical Uncertainty	23
2.4.3 Measurement Uncertainty	24

2.5	QUANTIFYING GEOTECHNICAL UNCERTAINTY	26
2.5.1	Classical Descriptive and Inferential Statistical Analysis.....	26
2.5.2	Second Moment Statistics	28
2.5.3	First Order Second Moment (FOSM) Method.....	29
2.6	SPATIAL CORRELATION ANALYSIS	30
2.7	RANDOM FIELD MODELLING OF SOIL VARIABILITY	33
2.8	QUANTIFICATION OF THE RELIABILITY OF SITE INVESTIGATIONS IN RELATION TO THE DESIGN OF FOUNDATION	34
2.8.1	Simulation of 3-Dimensional Random Field	36
2.8.2	Target Distribution and Correlation of Simulated Soil	36
2.8.3	Local Average Subdivision (LAS) Method	38
2.8.4	Transformation of Generated Soils	39
2.8.5	Soil Parameter and Reduction Techniques.....	42
2.8.6	Effect of Site Investigations on the Design of Pad Foundations.....	43
2.9	SUMMARY	43
 Chapter 3. Description of Research Method		45
3.1	INTRODUCTION	45
3.2	SOIL PROFILE SIMULATIONS	45
3.2.1	Size of Simulated Sites.....	47
3.2.2	Site Investigations	48
3.2.3	Type of Soil Test.....	51
3.3	PILE FOUNDATION DESIGN METHODOLOGY	52
3.4	MONTE CARLO SIMULATIONS	53
3.4.1	Metrics.....	53
3.4.2	Number of Realisations	54
3.5	VERIFICATION OF THE METHOD	54
3.5.1	Verifying the Model of the 3D Random Field	55
3.5.2	Verifying the Implementation of the LCPC Method	61
3.5.3	Verifying the Implementation of Monte Carlo Simulations	62
3.6	SUMMARY	63

Chapter 4. Effect of Radial Distance of a Single CPT Sounding on the Probability of Under- and Over-Design of a Pile Foundation.....	65
4.1 INTRODUCTION.....	65
4.2 SOIL VARIABILITY.....	66
4.3 TYPE AND SIZE OF PILE FOUNDATIONS.....	73
4.4 MEAN OF SOIL RESISTANCE VALUES.....	77
4.5 ANISOTROPIC SOILS.....	78
4.6 SUMMARY.....	80
Chapter 5. Effect of the Number of CPTs Used in Site Investigations on the Probability of Under- and Over-Design of Pile Foundations..	83
5.1 INTRODUCTION.....	83
5.2 SOIL VARIABILITY.....	83
5.3 NUMBER OF PILES.....	90
5.4 REDUCTION TECHNIQUES.....	94
5.5 ANISOTROPIC SOIL.....	95
5.6 SUMMARY.....	97
Chapter 6. Summary and Conclusions.....	99
6.1 SUMMARY.....	99
6.2 RECOMMENDATIONS FOR FUTURE RESEARCH.....	100
6.3 CONCLUSIONS.....	101
References.....	103
Appendix A.....	115
Appendix B.....	120
Appendix C.....	123

List of Figures

Figure 2-1	Traditional phases of characterisation of ground conditions	7
Figure 2-2	Schematic of cone penetration test	9
Figure 2-3	Schematic of standard penetration test (SPT)	11
Figure 2-4	Four different sampling patterns: (a) regular (square); (b) stratified random; (c) simple random and (d) stratified systematic unaligned	12
Figure 2-5	Herringbone sampling patterns	13
Figure 2-6	Diagram of method used to determine q'_{ca}	20
Figure 2-7	Integrated descriptive and inferential analysis for probabilistic modelling of a random variable	27
Figure 2-8	Flowchart of simulations	35
Figure 2-9	Elastic Modulus Values for a Soil COV of 50% and SOF of (a) 1 m, (b) 2 m, (c) 4 m, (d) 8 m, (e) 16 m, and (f) 32 m.....	37
Figure 2-10	Matrix of LAS	39
Figure 2-11	Sample (a) mean and (b) standard deviation of elastic modulus values at the surface ($z=1$) from a simulated soil with a COV of 50% and a SOF of (i) 1 m, (ii) 4 m and (iii) 16 m.....	40
Figure 2-12	Sample (a) mean and (b) standard deviation of elastic modulus values using field translation and a soil with a COV of 50% and a SOF of (i) 1 m, (ii) 4 m and (iii) 16 m	41
Figure 3-1	Flowchart of simulations	46
Figure 3-2	Simulation of various radial distances of a CPT	50
Figure 3-3	Plan of simulated pile foundations	50
Figure 3-4	Site Investigation schemes	51
Figure 3-5	Effect of target soil COV on the sample (a) mean and (b) standard deviation	57
Figure 3-6	Effect of target soil SOF on the sample (a) mean and (b) standard deviation	58
Figure 3-7	Sample standard deviation of soil resistance for different	

	SOFs	59
Figure 3-8	Correlation structure of simulated field for the soil with COV of 50% and (a) SOF of 1 m and SOF of 10 m.....	60
Figure 3-9	Correlation structures of simulated soil for (a) increasing target SOF and (b) increasing target COV	61
Figure 3-10	Probability of design error using Monte Carlo simulation.....	63
Figure 4-1	Plan view of the grid layout used for the simulated 3D data	67
Figure 4-2	Effect of radial distances on the probability of (a) under- and (b) over-design, for an increasing soil COV and a SOF of 1 metre	68
Figure 4-3	Effect of radial distances on the probability of (a) under- and (b) over-design, for an increasing soil COV and a SOF of 10 metres	69
Figure 4-4	Effect of radial distances on the probability of (a) under- and (b) over-design, for an increasing soil SOF and a COV of 50%.....	71
Figure 4-5	Critical distances for an increasing SOF, COV is set to 50%.....	72
Figure 4-6	Influence factor of the length of pile foundation on (a) the probability of under- and (b) over-design for the soil with SOF of 10 metres and a COV of 50%.....	74
Figure 4-7	Influence factor of the diameter of pile foundation on (a) the probability of under- and (b) over-design for the soil with SOF of 10 metres and a COV of 50%.....	75
Figure 4-8	Influence of the type of pile foundation on (a) the probability of under- and (b) over-design for soil with a SOF of 10 metres and COV of 50%	76
Figure 4-9	Influence factor of the mean of soil resistance values on (a) the probability of under- and (b) over-design for the soil with SOF of 10 metres and COV of 50%.....	78
Figure 4-10	Effect of the anisotropic soil on (a) the probability of under- and (b) over-design for soil with a COV of 50%	80
Figure 5-1	Plan view of site with 9 piles.....	84
Figure 5-2	Site Investigation plans examined.....	85
Figure 5-3	Effect of samplings efforts on the probability of (a) under-	

	and (b) over-design, for an increasing soil COV and a SOF of 1 metre.....	86
Figure 5-4	Effect of sampling efforts on the probability of (a) under- and (b) over-design, for an increasing soil COV and a SOF of 10 metres	87
Figure 5-5	Effect of sampling on the probability of (a) under- and (b) over-design, for an increasing soil SOF and a COV of 50%	89
Figure 5-6	Effect of SOF on the optimum number of boreholes of (a) under- and (b) over-design, for an increasing soil COV	90
Figure 5-7	3D soil profiles: (a) small SOF (random soil profiles), (b) large SOF (continuous soil profiles) (After Jaksa et al., 2005).....	91
Figure 5-8	Effect of the number of piles on the probability of (a) under- and (b) over-design, for different averaging methods on the soil with a COV of 50% and a SOF of 10 m.....	93
Figure 5-9	Effect of sampling effort on the probability of (a) under- and (b) over-design, for different averaging methods on the site with a COV of 50% and a SOF of 10 m.....	94
Figure 5-10	Effect of sampling efforts on the probability of (a) under- and (b) over-design, for isotropic and anisotropic soils.....	96
Figure B-1	Effect of radial distances on the probability of (a) under- and (b) over-design, for an different length of piles (COV of 50%, and SOF of 1 metre).....	120
Figure B-2	Effect of radial distances on the probability of (a) under- and (b) over-design, for an different length of piles (COV of 50%, and SOF of 20 metres)	121
Figure B-3	Effect of radial distances on the probability of (a) under- and (b) over-design, for an different length of piles (COV of 50%, and SOF of 100 metres)	122
Figure C-1	Effect of sampling efforts on the probability of (a) under- and (b) over-design, for an increasing COV (SOF of 20 metres).....	123
Figure C-2	Effect of sampling efforts on the probability of (a) under- and (b) over-design, for an increasing COV (SOF of 100 metres)....	124

List of Tables

Table 2-1	Dynamic methods	15
Table 2-2	Shio and Fukui Method (1982)	17
Table 2-3	Summary of CPT-based methods	18
Table 2-4	Determination of factor k_c based on pile type and nature of the soil	21
Table 2-5	Determination of coefficient α and maximum soil skin resistance based on pile types and the nature of soil	21
Table 2-6	Variability of soil properties	22
Table 2-7	Statistical uncertainties of various sites	24
Table 2-8	Measurement error of geotechnical tests	25
Table 2-9	Theoretical autocorrelation functions used to determine the scale of fluctuation	32
Table 3-1	Matrix of simulations	47
Table 3-2	Time-run for 1 realisation of the simulation	48
Table 3-3	mean of q_c values of the simulations	52
Table 3-4	Comparison between target and sample mean and standard deviation of simulated soils	56
Table 3-4	Comparison between pile load capacity using simulation program and the spreadsheet Microsoft <i>Excel</i>	62
Table 5-1	Coordinates of piles	84
Table 5-2	Number of piles for the simulations	92
Table 5-3	Isotropic and anisotropic soil	96

Notation

A_n	Net sectional area of pile toe
A_b	Cross-sectional area of pile base
APS	Australian Partnership Scholarship
A_{si}	Surface area of the pile shaft in contact with the soil
A_s	Gross surface area of the pile shaft
ASTM	American Standard of Testing Materials
CK	Complete Knowledge
CLPD	Centre of Learning and Professional Development
COV	Coefficients of variation
CPT	Cone Penetration Test
D	Diameter or width of the pile
DFT	Discrete Fourier transform
DMT	Dilatometer test
E	Young Modulus
FFT	Fast Fourier transform
f_i	Average unit skin friction of the soil layer i
FOSM	First order second moment
f_s	Sleeve friction of the CPT
f_{su}	Ultimate friction value along the pile shaft
GA	Geometric average
GIS	Geographic information system
GLS	Generalised least-squares
i	Soil layer

HA	Harmonic average
i^{+h}	Distance between the two points, X^i and X^{i+h}
KBS	Knowledge Base System
k_c	Penetrometer load capacity factor
LAS	Local average subdivision
LCPC	Laboratoire Central des Ponts et Chaussées, France
LFRD	Load and resistance factor design
MA	Moving average
m_ψ	Sample mean
n	Number of soil layers along the pile shaft
N	SPT number
N_b	Standard penetration number, N , at pile base
n_t	total population size
OLS	Ordinary least-squares
P	Probability of over-design or under-design
PDA	Pile driving analyser
Q_{all}	Allowable load capacity of a single pile
Q_b	Ultimate load at the pile base
Q_{CK}	Pile load capacity based on the complete soil properties
q_b	Unit load at the pile base
q_c	Cone tip resistance
q_{eq}	Equivalent cone resistance at the level of the pile tip
Q_s	Ultimate load along the pile shaft
Q_{SI}	Pile load capacity based on site investigations
q_u	unit load of the pile
Q_{ult}	Ultimate load of the soil at the pile base
q_s	Limit unit skin friction at the level of the layer i , and l_i

R_d	Radial distance between a borehole and a pile
SA	Standard arithmetic average
SAPAC	South Australian Partnership for Advanced Computing
SF	Safety factor
SI	Site investigation
SOF	Scale of fluctuation
SPT	Standard penetration test
TBM	Turning bands method
TT	Triaxial test
$Var(\mu)$	Variance of the sample mean
W	Weight of pile
$X(x + \tau)$	Sample at a distance τ from position x
$X(x)$	Sample at position x
X_i	Value of property X at location i
X_{i+h}	Value of property X at location
X_{ln}	Log normal variable
μ	Mean
$ \tau_j $	Separation distance
$\xi(z)$	Soil property
σ^2	Sample standard deviation
σ_e^2	Variance of equipment errors
δ_l	Estimated displacement
ρ_{ij}	Correlation coefficient between the i^{th} and j^{th} sample
σ_m^2	Total variance of measurement
σ_p^2	Variance of procedural errors
σ_r^2	Variance of random errors
σ_{sv}^2	Variance of soil variability

θ	Scale of fluctuation
Ψ	Sample data
μ_{lnx}	Mean of log normal variable
σ_{lnx}	Standard deviation of log normal variable