ULTIMATE PILE CAPACITY OF BORED PILE AND DRIVEN PILE AT ARA DAMANSARA USING BAYESIAN INVERSE METHOD

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by

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CERTIFICATION OF APPROVAL

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Approved by,

(Assoc. Prof. Dr. Indra Sati H. H.)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

June 2010

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.

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(CALVIN JONES JUSTIN)

ABSTRACT

The theoretical, semi-empirical, and empirical methods to design the ultimate pile capacity are widely used. However, the uncertainties of the soil parameters sometimes could lead to overestimation of ultimate pile capacity which makes the increasing of the cost of the project. This paper presents the analysis of the actual and designed ultimate pile capacity, and the application of Bayesian approach for inverse analysis as a method to obtain the unit shaft resistance and the unit base resistance based on the pile load test results at Ara Damansara. The result for this project is limited to the area around Ara Damansara only. In this paper, comparison of unit shaft resistance and unit base resistance between bored pile and driven pile were done. Prior knowledge for unit shaft resistance and unit base resistance are based on Standard Penetration Test (SPT) N value. From the prior knowledge, Bayesian approach can be applied to obtain the new ultimate pile capacity based on the pile load test results. The Bayesian approach can be updated when new information is obtained, therefore further to reduce the uncertainty of the unit shaft resistance and unit base resistance. Thus, the ultimate pile capacity can be design more accurate by applying Bayesian approach as part of the design tool.

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CHAPTER 1

INTRODUCTION

1.1 Background of Project

The result of the pile load test results were obtained at a construction site at Ara Damansara (Selangor, Malaysia). The ongoing construction was led by a registered contractor with class A license and the company is one of the largest construction company in Malaysia.

During the construction, bored pile (also known as drilled shafts) (Huat & Pavadai, 2006b) and driven pile (in this project is driven precast reinforced concrete square pile) has been used as the structures foundation. Pile load test has been conducted to ensure the settlement of the top pile is within the limit that has been specified. Usually there will be two types of pile load test which are preliminary pile load test and working load test pile. Preliminary pile load test is to test the pile to failure (based on failure criteria as specified by the Public Works Department (2005)) to confirm the actual ultimate pile capacity and normally will only be done once for a different diameter at a certain location, depending on the soil investigation results. The working load pile test is done depends on the cost and requirement of the project. The working load pile test is usually tested twice the design load at a constant rate of loading at least 2 load cycles. In special cases, the working load pile test is tested 3 times the design load.

For this project, by using the Bayesian approach as inverse analysis the ultimate pile capacity from the pile load test results will be analyze to obtain the new unit shaft resistance, and unit base resistance. Therefore, the ultimate pile capacity is updated to be more accurate.

1.2 Site Condition

A total of 10 bore holes were carried out for soil investigation during the preliminary stage. The soil investigations were carried out by using Standard Penetration Test (SPT). Unconfined compressive strength test on rock core according to ASTM D2938-86 were also done. The site condition was mainly formed by 2 types of soil, which were sand and silt. Sand was found on the top of the soil layer while very stiff or hard sandy silt were encountered on the next layer. Granite was found in three bore holes with average RQD range 12% - 48%.

1.3 Problem Statement

There are various types of method (theoretical, empirical and semi-empirical methods) in designing the ultimate pile capacity (Al-Homoud et al., 2004). The outcome of these methods varies and could cause a high possibility to confuse the client if comparison is done. In other words, the unit shaft resistance and the unit base resistance have a lot of uncertainties in predicting it. Sometimes these methods could overestimate the ultimate pile capacity of bored pile and driven pile which will increase the cost of a project. Comparison has been made by Al-Homoud et al. (2003) and shows that some of the methods over predicted the ultimate pile capacity. The construction of bored pile and driven pile also give different unit shaft resistance and unit base resistance.

The results obtained by previews pile load test were not been analyse to improve the design ultimate pile capacity for a particular project. The data will only be kept because the design methods which are mostly being used now do not consider the previews test result to update the pile capacity. The data obtained are actually work done at the site which requires some cost and have useful information to improve the accuracy of the ultimate pile capacity. Therefore, it is wasteful if the previews pile load test are not been make use or take into consideration for improvement of designed ultimate pile capacity.

1.4 Objective and Scope of Study

1. To obtain the updated unit shaft resistance and unit base resistance based on pile load test result using Bayesian inverse method.
2. To compare and analyze the results obtained from the Bayesian inverse method between bored pile and driven pile

This project is based on the results obtained from the construction project near Ara Damansara. Therefore the result of this project is only applicable around Ara Damansara that has the similar soil condition. Only 600mm diameter bored pile and 400mm x 400mm precast driven reinforced concrete square pile will be considered in this project. The interpretation of ultimate pile load capacity is based on Davisson's criteria as in (Choon & Sing, 2008; Abdelrahman et al, 2003). The time effect of the pile capacity is not considered. The result obtained from Bayesian inverse method will only be compared to other empirical methods that are based on SPT N value.

1.5 Relevancy and Feasibility of the Project

In terms of scope of study, this project is relevant since it involves mainly on the study of the foundation and earth structures, and probability and statistics. This project involves the design of bored pile and driven pile load capacity by which it can increase the accuracy of the design. Therefore, it is relevant since it can be a new tool for obtaining the unit shaft resistance and the unit base resistance.

This project requires spreadsheet software, in this project Microsoft Excel 2007 and Mathematica 6 will be utilized for analysis of the database. The pile load test results can be obtained from the companies that conducted the pile load test. This is therefore a low cost project but yet, it can save cost for construction project that applies this project's method to obtain the unit shaft resistance and unit base resistance. This project can be referred by institutions and companies as part of their supporting data regarding ultimate pile capacity. Engineers can also refer to this method to update the unit base resistance and unit shaft resistance, thus obtaining the ultimate pile capacity. By this, the total cost of foundation construction can be reduced.

CHAPTER 2

LITERATURE REVIEW

2.1 Bored Pile

Bored pile has been widely used in Malaysia and the applied diameter has been used up to 3.0m (Tan et al., 2009). The design bored pile capacity shown by Tan & Meng (2003) and Huat & Pavadai (2006b) are mainly applied in Malaysia. There are two mostly used types of construction method of bored pile which are wet method and dry method. Study has been done by Chen & Hiew (2006) to compare the performance of the bored pile in different construction and found that shaft friction is higher by using dry method. One of the advantages according to Huat & Pavadai (2006b) is that engineers can obtain soil parameters from the bored soil and this will allow them to confirm whether the soil parameters used to design the ultimate pile capacity are similar or different. It is recommended that in designing bored pile capacity, shaft resistance is only considered. Base resistance is not considered in designing because it is difficult to have a consistent base cleaning (Tan & Meng, 2003).

2.2 Driven Pile

There are many types of driven pile being used nowadays. In this project, reinforced concrete (RC) square piles were used. Square pile can be cast in-situ or pre-cast. Like bored pile, square pile can be friction pile and end bearing pile. However, bored pile has lower end bearing capacity compare to driven pile because the construction of bored pile has weaken the soils that are contacted with the pile tip (Huat & Pavadai, 2006a). To get rough idea whether the pile capacity at the field has reached the design pile capacity, Hiley's formula is normally adopted by referring on the pile set/blow. However, pile capacity can only be verified by maintained load test and pile dynamic analyzer (Gue, 2007).

2.3 Ultimate Pile Capacity

There are several methods to design the ultimate pile capacity of bored pile. Empirical, semi-empirical, theoretical methods are widely use. Al-Homoud et al. (2003) has made a comparison between designed and actual values of axial end bearing and skin capacity of bored pile in cohesionless soils in the Arabian Gulf Region. The results found that the methods used such as Janbu's theoretical method (1989) is accurate in terms of base resistance. For empirical method, Reese (1989) is more accurate than Meyerhof (1976) for base resistance for bored pile. However, the skin resistance predicted is considered inaccurate. In Matera, Italy, study has been conducted to compare the ultimate pile capacity of bored pile between the theoretical method and actual capacity by Cherubini et al.(2005) and found that the actual pile capacity satisfies the theoretical method if the pile is completely bored into the Matera clay. This shows that the results varied and there are uncertainties of soil parameters.

Based on Meyerhof (1976), the unit shaft resistance, f_s =1.0xSPT'N' for bored pile and f_s = 2.0xSPT'N' for driven pile. The unit base resistance, q_b = (20L/D) x SPT'N' $\leq$ 300 x SPT'N' for driven pile and q_b = (13L/D) x SPT'N' $\leq$ 300 x SPT'N' for bored pile, where A_b is the pile base area, L is the average length of pile, and D is the diameter of pile. Reese (1989) empirical method for unit base resistance for bored pile in this project is q_b = 120 x SPT'N'.

According to Gue (2007), by using modified Meyerhof (1976), f_s is 2.5xSPT'N' and the unit base resistance, q_b is 250xSPT'N' for cohesive soil, whereas in cohesionless soil, f_s=2.0xSPT'N' and q_b = (250 to 400) x SPT'N'. He also said that base resistance should be ignored for bored pile if it is uncertain. The ultimate pile capacity increase with time (Liew & Kwong, 2005), therefore the time of installation of piles and time of testing the piles is one of the factor that varies with the predicted pile capacity (Chen et al., 1999). In (Phienwej et al., 1994), K_s = 2.3 for SPT'N' values below 120.

According to Chen & Hiew, 2006:

> "Tan et al, (1998), after studying 13 bored piles constructed using either the dry or the wet method, suggested addopting $K_s = 2$ for design purposes, and limiting the maximum unit shaft friction to not more than 150 kPa." p.227

For driven pile, $K_s = 2.5$ and $K_b = 250$ to 350 for preliminary assessment in silt and sandy silt (Tan et al., 2009). In (Shariatmadari et al., 2008), for sandy silt, $K_s = 2.5$ and $K_b = 245$

2.4 Pile Load Test

Comparison of result of settlement between pile dynamic analysis (PDA) test and maintained load test (MLT) studied by (Chen & Lim) shows that the maintained load test gives higher settlement. Another comparison between PDA, maintained load test and statnamic test were done by (Hajduk et al., 2004). It shows that PDA and maintained load test are more suitable to determine the ultimate pile capacity. According to Briaud et al., (2000):

> "...dynamic methods do not give a consistently accurate acceptable working loads for piles without unusual conditions." p.648

In (Al-Homoud et al., 2003) and (Cherubini et al.,2005) research, MLT were applied for the comparison of the empirical method. The amount of usage of maintained load test is less than PDA test because of time consuming and more expensive (Chen & Lim). Based on research done, Chin's method and Davisson's criterion are usually been used to interpret the ultimate pile capacity for maintained load test. Briaud et al. (2000) and Hajduk et al. (2004) used Davisson's criterion to determine the ultimate pile capacity. Cherubini et al. (2005) used Chin's method as one of their tools for ultimate pile capacity interpretation. In this project, the method to interpret the ultimate pile capacity is by using Davisson's Criterion.

2.5 Bayesian Statistics

There are a lot of studies have been conducted by various researches in addressing the similar approach to solve the variation and uncertainties of soil parameters such as Miranda et al. (2009) regarding the underground structures. University Teknologi PETRONAS also have used Bayesian approach to obtain ultimate pile capacity from the posterior information for socketed drilled shaft (Harahap & Wong, 2008). Harahap and Wong (2008) found out that using Markov Chain Monte Carlo (MCMC) method is more accurate than Monte Carlo (MC) method. In 2004, Zhang et al. (2004) say that it would be better if the site information will be taken into consideration in conjunction with global information. This is because different region will have different soil parameters. To reduce the uncertainty of the prediction of the pile capacity, Bayesian approach has been used.

According to Zhang et al. (2004):

> The Bayesian approach "which incorporates regional and site-specific observations into the design to reduce variability in a rational manner, can be done effectively by taking advantage of regional experience and quality assurance programs within the design" p.527

Not long ago, Ditlevsen et al. (2000) also addressed the same problem that has been faced by geotechnical engineers which is the uncertainties of soil parameters. They use Bayesian to estimate the soil parameters, thus reduced the uncertainties. By reducing the uncertainties, they obtained more accurate pile capacity.

There are other application of Bayesian approach for uncertainty reduction and updating information like Li et al. (2008). They used Bayesian approach to predict the probability occurrence of the size of defect of bored pile and update it when new information is received.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

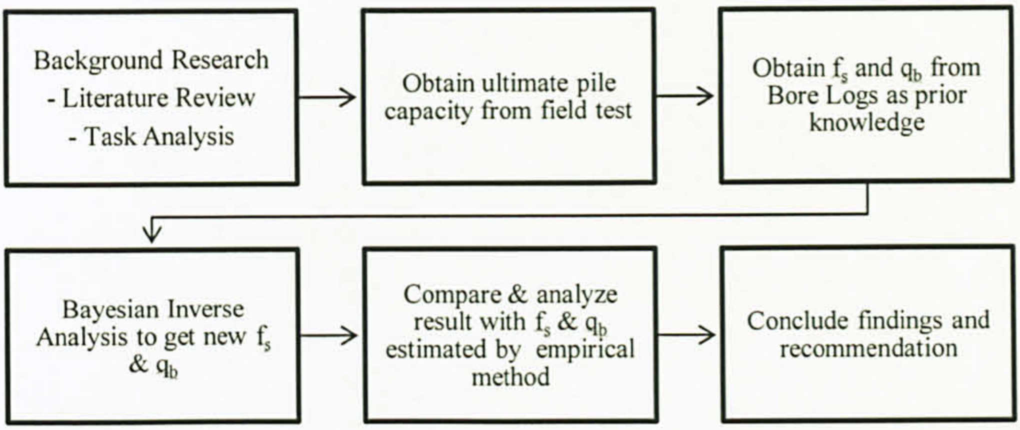

Figure 1: Research Methodology

3.1.1 Design of Pile Foundation in soil

The design of bored pile and driven pile is important to obtain the designed ultimate shaft capacity and the ultimate base capacity. There are a lot of models widely used to design the ultimate capacity of pile foundations such as Meyerhof (1976) empirical approach, Vesic's (1970) empirical approach, and Burland (1973) approach (Al-Homoud et al., 2003). However, in this project, only some empirical approach based on SPT'N' value will be compared with the Bayesian inverse method result.

The ultimate capacity of bored pile and driven pile can be determined using the following equation:

$$Q_u = Q_s + Q_b$$

$$Q_u = f_s A_s + q_b A_b \qquad (1)$$

Where Q_u is ultimate pile capacity, Q_s is ultimate shaft capacity, Q_b is ultimate base capacity. The ultimate shaft capacity consists of unit shaft resistance, f_s which is the friction between the pile and the soil, A_s is the circumferential area of pile embedded in each layer of soil. q_b is unit base resistance for the bearing layer of soil and A_b is the pile base area. Semi-empirical method and simplified soil mechanics methods are commonly used in Malaysia (Tan & Meng, 2003). The unit shaft resistance and unit base resistance in semi-empirical method are $f_s = K_s$ x SPT'N' and $q_b = K_b$ x SPT'N', where K_s is ultimate shaft resistance factor, K_b is ultimate base resistance factor and SPT'N' is standard penetration test blow counts (blows/300mm). If the bored pile is socketed to an impervious bed rock, semi-empirical method from the Rock Quality Designation (RQD) is normally used in Malaysia (Tan & Meng, 2003). The simplified soil mechanics method in variation of stress level for unit shaft resistance is $f_s = K_{se}\, \sigma_v \tan \phi$, where K_{se} is the effective stress shaft resistance factor, σ_v is vertical effective stress and ϕ is friction angle (Tan & Meng, 2003). For undrained method, $f_s = \alpha$ x s_u, where α is adhesion factor and s_u is undrained shear strength, whereas for coarse grained, $f_s = \beta$ x σ_v, where β is the shaft resistance factor for coarse grained soil (Tan & Meng, 2003). The base resistance for simplified soil mechanics is $q_b = N_c$ x s_u where N_c is the bearing capacity factor. In this project, semi-empirical method is used.

3.1.2 Pile Load Test

The procedure of pile load test which includes the type of pile load test (failure load test or preliminary load test and working load test) is based on the PWD (2005). The interpretation of ultimate pile capacity can be done by using Davisson's criterion, Chin's method, by projection of load settlement curve and others. In this project, Davisson's criterion is used for the interpretation.

3.1.3 Probabilistic Inverse Method

Supposed f is the function that map parameters into theoretical quantity such that d = f(m) where d = $\{d^i,...,d^{ND}\}$ and m = $\{m^i,...,m^{NM}\}$, thus the objective of inverses analysis is to determine m given d. In terms of pile load test, the inverse analysis is to determine f_s, and q_b knowing Q_u obtained from pile load test and f is the relationship in Eq. (1).

Suppose that the observed data values is d_{obs}, the probability density model to describe experimental uncertainty by Gaussian model can be written as follow

$$\rho_D(d) = k\exp\left(-\frac{1}{2}(d-d_{obs})^T C_D^{-1}(d-d_{obs})\right) \tag{2}$$

where C_D is the covariance matrix. If the uncertainties are uncorrelated and follow Gaussian distribution, it can be written as

$$\rho_D(d) = k\exp\left(-\frac{1}{2}\sum\left(\frac{d^i-d^i_{obs}}{\sigma^i}\right)^2\right) \tag{3}$$

In usual problem the model parameters have complex probability distribution over the model space. The probability density is marked as $\rho_M(m)$. Suppose that joint probability function is known $\rho(m,d)$ and d = f(m), then the conditional probability density function, $\sigma_M(m) = \rho_{M|d(m)}(m \mid d = f(m))$ can be obtained as follow (Mosegaard & Tarantola, 2002).

$$\sigma_M(m) = k\rho_M(m)\left.\frac{\rho_D(d)}{\mu_D(d)}\right|_{d=f(m)} \tag{4}$$

where k is the normalizing factor, $\mu_D(d)$ is homogeneous probability density function, and linear which upon integration over the data space become unity.

3.1.4 Evaluation of Posterior Distribution

The analytical form of posterior distribution is difficult to interpret. It becomes more complex when thousands of samples are interpreted. There are two approaches to overcome this difficulty which are Monte Carlo simulation and Markov Chain Monte Carlo (MCMC). Monte Carlo simulation can obtain parameter pairs over the model space and used such data for any application. After sufficient number on sampling of random variables X_0, X_1,..., X_n the expectation $\mu = E\{g(X_i)\}$ is approximated as:

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} g(X_i) \tag{5}$$

MCMC approach the sequence of random variables X_0, X_1, X_2,... at each time $t \geq 0$ the next state X_{t+1} is sampled from a distribution $P(X_{t+1} \mid X_t)$ that depends on the state at time t. The approximation process is similar to Monte Carlo simulation.

3.15 Bayesian Interpretation of Pile Load Test Result

The model of ultimate pile capacity of bored pile and driven pile in soil is given by Eq. (1). Assuming the pile geometry is known, the model space is then m = (f_s,q_b). The probability density model to describe experimental model (Eq. 3) is formed using the theoretical model d = f(m) as in Eq. (1), and observed pile ultimate capacity d_{obs}. The joint probability density is then $\sigma_M(m) = \sigma_M(f_s,q_b)$.

$$\sigma_Q(f_s) = \int_e^d [\sigma_M(f_s, q_b)] dq_b$$

$$\sigma_Q(q_b) = \int_e^d [\sigma_M(f_s, q_b)] df_s$$

where d and e is the limiting value.

Prior knowledge can be incorporated in $\rho_M(m) = \rho_M(f_s,q_b)$ particularly knowledge on those parameters specific for the soil type and its region. For bored pile, the prior knowledge for f_s is 90 kPa, obtained from $K_s = 2$ and average SPT'N' = 45. It is assumed that the design of bored pile does not consider the contribution of q_b as recommended by (Tan et al., 2009) and Gue (2007).

The f_s for driven pile will be 112.5 kPa with K_s = 2.5 and q_b will be 11250 kPa with K_b = 250. The K_s and K_b is based on (Tan et al., 2009). The average SPT'N' value is 45.

3.2 Project Activities and Tools

1. Research will be done according to the research methodology as in Figure 1.
2. Thorough study on Bayesian Statistics is crucial in this project. Therefore, the main reference for the study of Bayesian Statistics will be in (Bolstad, 2007) and (Mosegaard & Tarantola, 2002).

Computer is a must in this project. The software used for this project will be as follows:

a. Microsoft Office 2007 (Words and Excel)
b. Microsoft Project (this is for project management such as Gantt Chart)
c. Mathematica (for Monte Carlo simulation and MCMC simulation)

3.3 Gantt Chart (FYP 2)

ID	Task Name	Duration	Start	Finish	% Complete
1	**Final Year Project**	**336 days**	**Mon 20-07-09**	**Sat 30-10-10**	**99%**
2	**Final Year Project 1**	**161 days**	**Mon 20-07-09**	**Mon 01-03-10**	**100%**
26	**Final Year Project 2**	**199 days**	**Wed 27-01-10**	**Sat 30-10-10**	**95%**
27	**Project Work Continues**	**69 days**	**Wed 27-01-10**	**Mon 03-05-10**	**100%**
28	Analysis of Results and Interpretation	69 days	Wed 27-01-10	Mon 03-05-10	100%
29	Submission of Progress Report	1 day	Fri 12-03-10	Fri 12-03-10	100%
30	Project Work Continue	31 days	Mon 22-03-10	Mon 03-05-10	100%
31	Poster Exhibition	1 day	Wed 14-04-10	Wed 14-04-10	100%
32	Submission of Dissertation (Soft Bound)	1 day	Thu 06-05-10	Thu 06-05-10	100%
33	Oral Presentation	4 days	Mon 07-06-10	Thu 10-06-10	0%
34	Submission of Project Dissertation (Hard B	1 day	Sat 30-10-10	Sat 30-10-10	0%
35	**Seminars**	**36 days**	**Wed 17-02-10**	**Wed 07-04-10**	**100%**
36	IEM Talk	1 day	Wed 17-02-10	Wed 17-02-10	100%
37	Statistics for Engineers	1 day	Wed 24-02-10	Wed 24-02-10	100%
38	Why Graduate School?	1 day	Wed 07-04-10	Wed 07-04-10	100%

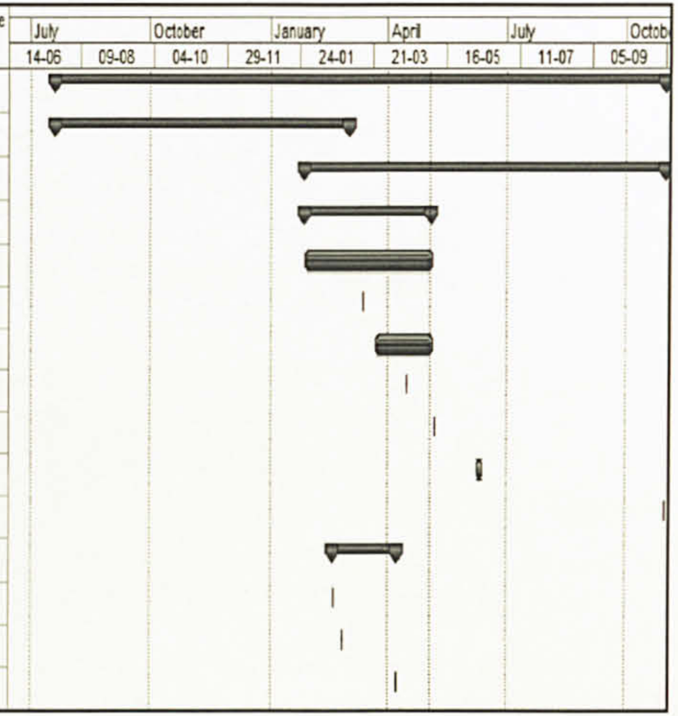

Figure 2: Gantt Chart (FYP 2)

CHAPTER 4

RESULTS AND DISCUSSION

A total of 312 bored piles with 600mm diameters and 1140 400mm square driven piles constructed as foundation at the site. Maintained load test (MLT) and pile dynamic analysis (PDA) test were carried out to ensure that the actual ultimate pile capacity conform to the design.

For bored pile, 2 MLT results were obtained, each tension load test and compression load test. 14 PDA test results were also obtained from the same site. The designed Q_s is 1050kN and the designed Q_u is 3000kN. For driven pile, 2 MLT results were obtained and both are compression load test, and 6 PDA test results were obtained from the same site and the designed Q_u is 2700kN.

4.1 Field Test Result

The piles are tested twice the allowable design load for MLT but for tension load test, the test is only 1.75 times the allowable design shaft load. The MLT is done in two cycles except for the bored pile (15/B-01) which was tested up to three cycles.

The results for MLT and PDA are shown in Table 1 below. The interpretation of ultimate pile capacity for MLT is done by using Davisson's criteria, 3.81mm + D/120 + PL/AE, where D is the diameter of pile or dimension, P is the load applied, L is the length of pile, A is the base area of pile, and E is the modulus of elasticity.

By back-calculating the tension load test, the f_s obtained is 33 kPa. Davisson's criteria can only interpret the ultimate pile capacity therefore the MLT results will not be back-calculated in this case. The PDA test results for bored pile shows that the lowest f_s is 42 kPa and the highest is 98 kPa. The q_b obtained from PDA test results shows that the lowest is 1450 kPa and the highest is 6225 kPa. For driven pile, the PDA test results shows that the lowest f_s is 47 kPa and the highest is 124 kPa, whereas for q_b, the lowest is 4938 kPa and the highest is 16750 kPa.

Table 1: Summary of MLT and PDA results

No.	Pile Name (Bored Pile)	Type of Test	Length, m	Q_u, kN
1	6/I-1	Maintained Load Test	19.900	3955
2	15/B-01	Tension Load Test	16.475	1020 (Q_s)
3	P15/E-2	PDA	16.100	3180
4	P-13/B-1	PDA	15.700	3310
5	P-14/C-3	PDA	15.800	3080
6	P-12/C-1	PDA	16.100	3600
7	P-2/B-1	PDA	21.000	3070
8	P-8/G-4	PDA	19.000	3080
9	P5/B-3	PDA	18.700	3250
10	P6/B-1	PDA	14.800	3190
11	P3/K-3	PDA	18.700	3940
12	P6/M-1	PDA	18.400	3450
13	P4/O-1	PDA	18.930	3210
14	9/O-P-2	PDA	19.000	3950
15	12/Q-3	PDA	18.800	3440
16	14/P-Q-3	PDA	19.200	3940
	Pile Name (Square Pile)	**Type of Test**	**Length, m**	**Q_u, kN**
1	9/C-4	MLT	12.000	2565
2	11/G-10	MLT	12.000	2570
3	10/E-7	PDA	12.000	3490
4	11/I-7	PDA	15.000	3850
5	13/I-3	PDA	15.000	3590
6	13/G-5	PDA	14.500	3660
7	4/C-2	PDA	12.880	3790
8	7E-2	PDA	10.980	3590

4.2 Bayesian Inverse Method Result

Comparison between "brute force" Monte Carlo (MC) and Markov Chain Monte Carlo (MCMC) of ultimate pile capacity for bored pile and driven pile is investigated. In this project, bored pile of 600mm diameter with average length 17.9m and driven pile (400mm x 400mm) with average length 13.0m were being investigated.

The plot of posterior probability density, sampling points generated by MC, and sampling points generated by MCMC is shown in Figure 3, Figure 4, and Figure 5 below. By comparing Figure 4 and Figure 5, sampling points generated by MCMC is more concentrated to the centre of the posterior distribution compare to sampling points generated by MC. When statistically compared, MCMC has smaller standard deviation compared to MC. This can be concluded that MCMC is more accurate than MC for Bayesian inverse method.

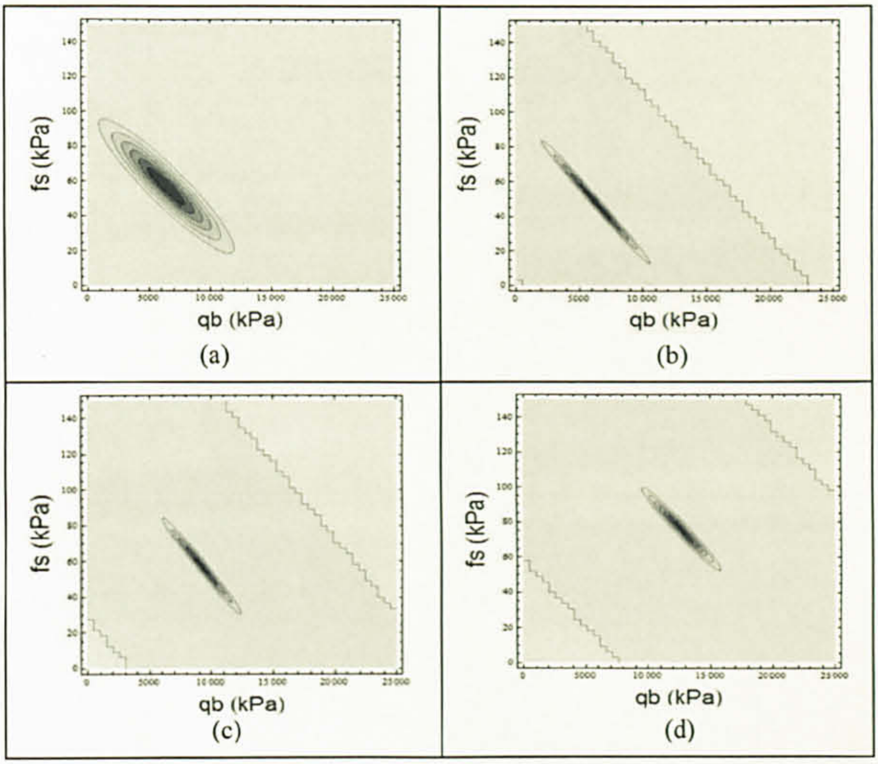

Figure 3: Posterior Distribution for (a) Bored pile (MLT), (b) Bored pile (PDA), (c) Driven pile (MLT), (d) Driven pile (PDA)

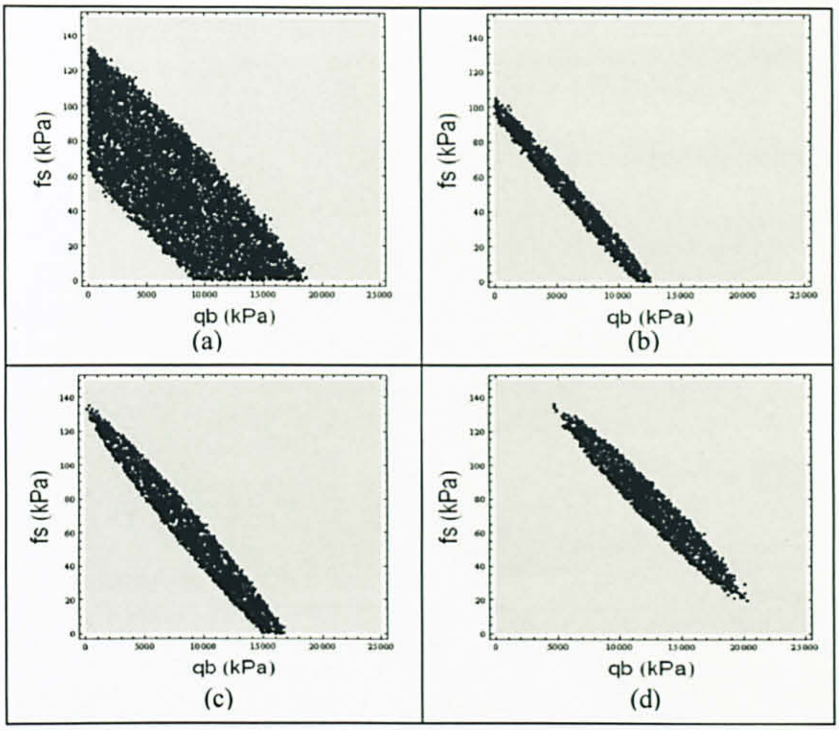

Figure 4: Sampling points generated by MC for (a) Bored pile (MLT), (b) Bored pile (PDA), (c) Driven pile (MLT), (d) Driven pile (PDA)

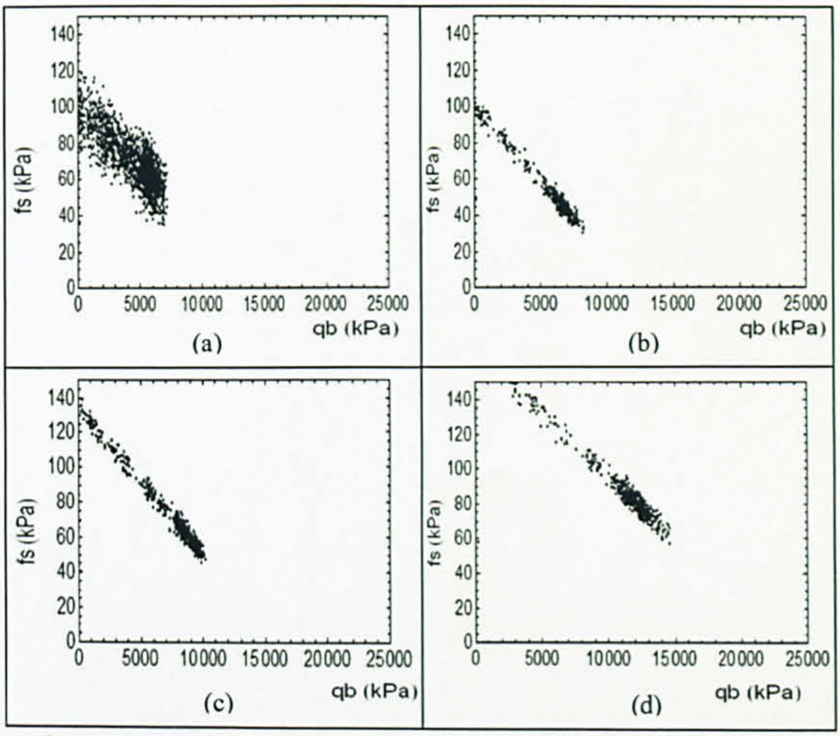

Figure 5: Sampling points generated by MCMC for (a) Bored pile (MLT), (b) Bored pile (PDA), (c) Driven pile (MLT), (d) Driven pile (PDA)

Table 2: Comparison of MC and MCMC for bored pile and driven pile

Type of pile	Remark	Mean (kN)	Median (kN)	Standard Deviation (kN)
Bored pile (MLT)	MC	3919	3983	811
	MCMC	3384	3413	222
Bored pile (PDA)	MC	3414	3414	144
	MCMC	3384	3338	101
Driven pile (MLT)	MC	2672	2672	148
	MCMC	2792	2785	34
Driven pile (PDA)	MC	3600	3600	135
	MCMC	3533	3517	83

The column chart in Figure 7 and Figure 8 below were derived from the Bayesian interpretation of the bored piles and driven piles with respect to type of test. The posterior distribution from Bayesian inverse method as in Figure 6 shows the shift of the f_s and q_b with respect to type of test and type of pile.

Based on Figure 6, in terms of MLT, bored pile has the same f_s with driven pile, but driven pile has higher q_b than bored pile with difference 2800 kPa. In terms of PDA, the results show that driven pile has higher f_s with difference 28 kPa and q_b with difference 6366 kPa compared to bored pile.

The results obtained from MLT and PDA varies could be because of the time effect of the ultimate pile capacity. With limited data available, it can be speculated that in terms of PDA, driven pile has high f_s and q_b could be because of the time effect whereby the pile capacity increases with time (Chen et al., 1999). However, according to Alvarez et al. (2006) by comparing the types of test, PDA results shows higher percentage of confidence level compare to MLT.

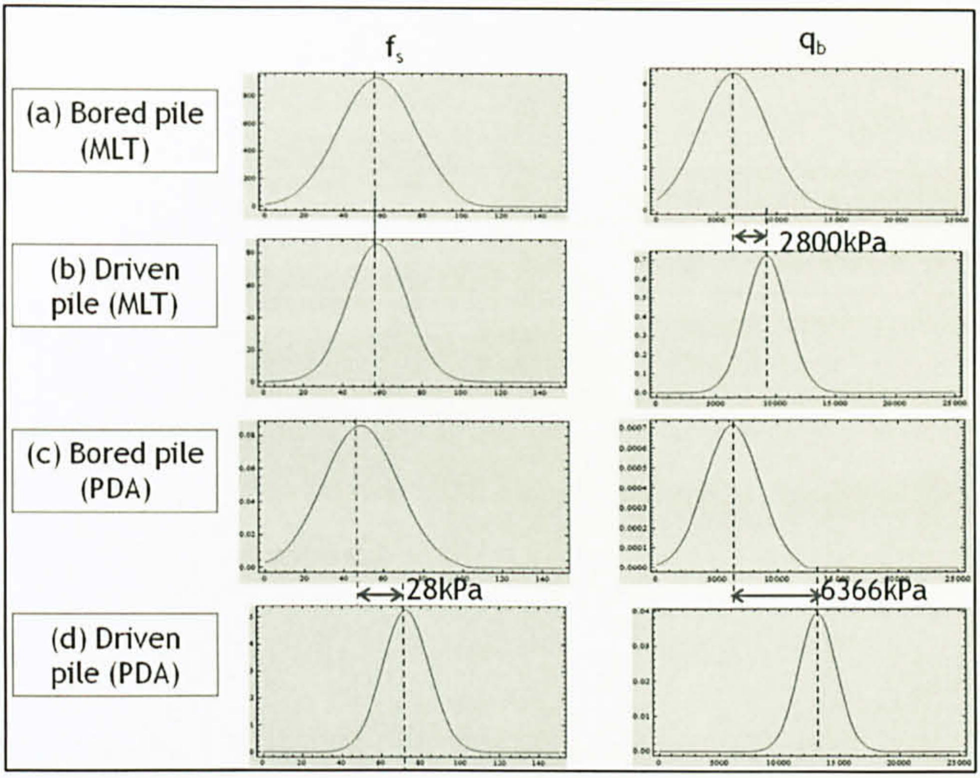

Figure 6: Posterior distribution of unit shaft resistance and unit base resistance

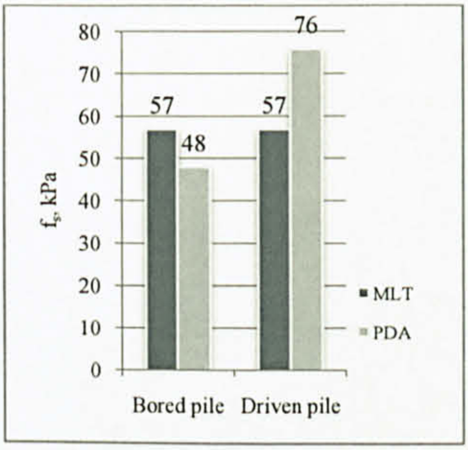

Figure 7: f_s interpreted using Bayesian Inverse Method

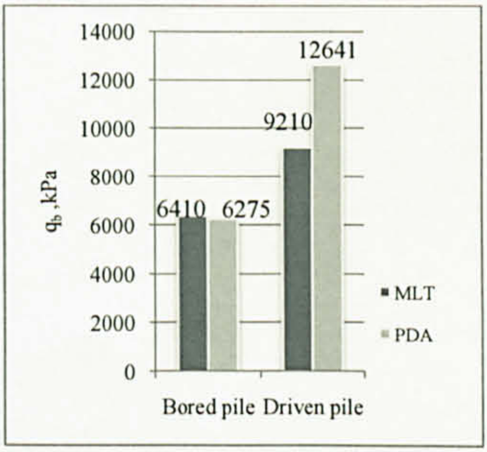

Figure 8: q_b interpreted using Bayesian Inverse Method

The K_s and K_b is then back-calculated for PDA results. The MLT results were interpreted using Davisson's criteria, therefore K_s and K_b is unable to be back-calculated. For bored pile, K_s is in the range of 0.93 to 2.13, and K_b is in the range of 32.2 to 138.3. For driven pile, K_s is in the range of 1.04 to 2.76 and K_b is in the range of 109.7 to 372.2.

Bayesian inverse method obtained K_s for bored pile within 1.1 to 1.3 and for driven pile, the K_s is within 1.3 to 1.7. The values of K_s obtained are lower than the value of K_s suggested (i.e K_s = 2.0 for bored pile and K_s = 2.5 for driven pile). The K_b for bored pile falls within 139.4 to 142.4 which is high compare to what has been discussed in (Tan et al., 2009) and (Chen & Hiew, 2006). On the other hand, the K_b for driven pile falls within 204.7 to 280.9 which the range is lower than the suggested K_b values (i.e. 250 to 350).

Comparison of f_s and q_b in terms of K_s and K_b are also done based on ratio of predicted, $K_{s(p)}$ and $K_{b(p)}$ (based on PDA result) to estimated, $K_{s(e)}$ and $K_{b(e)}$ (based on empirical methods and Bayesian approach) and also the percentage of the dispersion of the data as in (Al-Homoud et al., 2003).

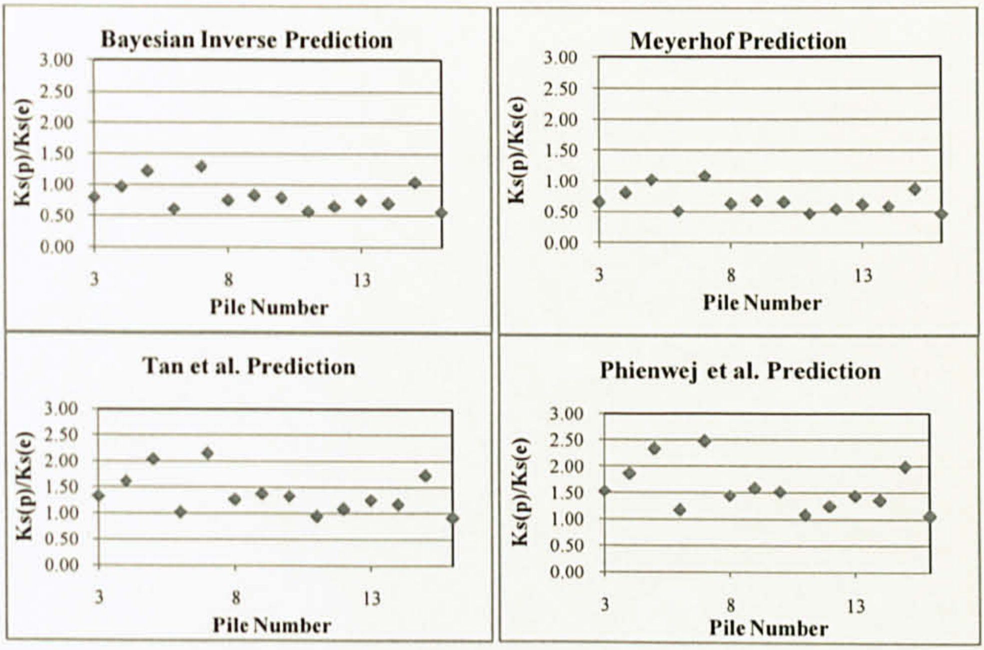

Figure 9: Ratio of predicted to estimated ultimate shaft resistance factor for bored pile

Table 3: Statistical comparison of predicted to estimated ultimate shaft resistance factor for bored pile

Prediction	Mean	Min	Max	Standard Deviation
Bayesian Inverse	0.823	0.554	1.295	0.230
Meyerhof (1976)	0.686	0.461	1.080	0.192
Tan et al (1998)	1.371	0.923	2.159	0.384
Phienwej et al (1994)	1.577	1.061	2.483	0.441

Table 4: Percentage of predicted to estimated ultimate shaft resistance factor for bored pile

Prediction	$K_{s(p)}/K_{s(e)} > 2.00$ (100%)	$0.8 < K_{s(p)}/K_{s(e)} < 1.2$ (±20%)	$0.6 < K_{s(p)}/K_{s(e)} < 1.4$ (±40%)
Bayesian Inverse	0.0%	21.4%	85.7%
Meyerhof (1976)	0.0%	28.6%	64.3%
Tan et al (1998)	14.3%	35.7%	71.4%
Phienwej et al (1994)	14.3%	21.4%	35.7%

Referring to Table 3 and Table 4 above, K_s suggested by Tan et al (1998) and Phienwej et al (1994) over predicted $K_{s(p)}/K_{s(e)} > 2.00$ by 14.3%. Meyerhof is considered reliable to estimate the unit shaft resistance since it has the lowest standard deviation (0.192) and 0.0% over predicted, but slightly under predicted (Mean = 0.686). The prior knowledge used in Bayesian inverse method is the K_s that Tan et al (1998) has suggested. The Bayesian inverse method has reduced its prediction error of Tan et al. (1998) with 0.0% over predicted and lower standard deviation (0.230). This shows that Bayesian inverse method is also reliable in estimating the unit shaft resistance for bored pile after Meyerhof (1976).

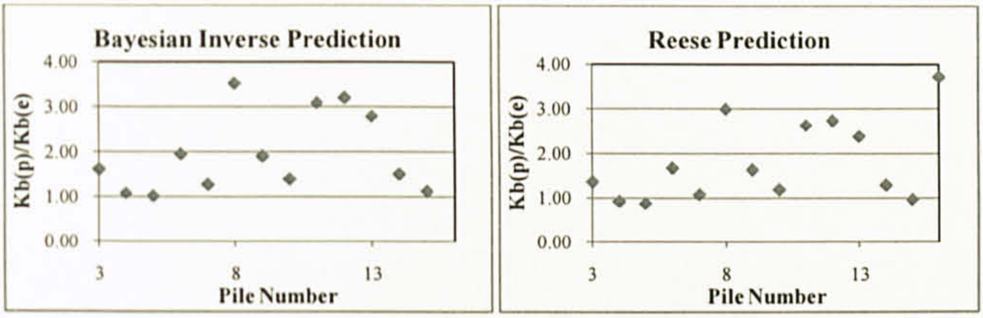

Figure 10: Ratio of predicted to estimated ultimate base resistance factor for bored pile

Table 5: Statistical comparison of predicted to estimated ultimate base resistance factor for bored pile

Prediction	Mean	Min	Max	Standard Deviation
Bayesian Inverse	2.130	1.019	4.373	1.070
Reese (1989)	1.814	0.868	3.724	0.911

Table 6: Percentage of predicted to estimated ultimate base resistance factor for bored pile

Prediction	$K_{b(p)}/K_{b(e)} > 2.00$ (100%)	$0.8<K_{b(p)}/K_{b(e)}<1.2$ (±20%)	$0.6<K_{b(p)}/K_{b(e)}<1.4$ (±40%)
Bayesian Inverse	35.7%	21.4%	35.7%
Reese (1989)	35.7%	35.7%	50.0%

Based on Table 5 and Table 6 above, Bayesian inverse method has higher standard deviation (1.070) and the mean (2.130) compared to Reese (1989). Reese (1989) over predicted ($K_{b(p)}/K_{b(e)} > 2.00$) by 35.7% as well as Bayesian inverse method. The result shows that Reese (1989) is more accurate than Bayesian inverse method; however it does not mean that it is no reliable. In this project, there is no prior knowledge being input for unit base resistance for bored pile.

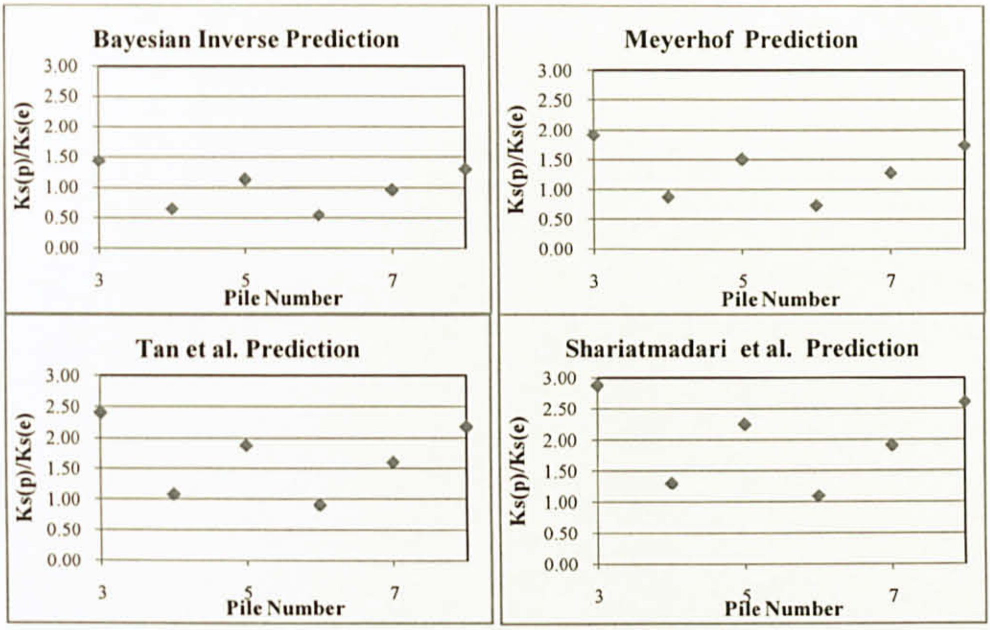

Figure 11: Ratio of predicted to estimated ultimate shaft resistance factor for driven pile

Table 7: Statistical comparison of predicted to estimated ultimate shaft resistance factor for driven pile

Prediction	Mean	Min	Max	Standard Deviation
Bayesian Inverse	1.004	0.546	1.440	0.356
Meyerhof (1976)	1.338	0.728	1.920	0.474
Tan et al (2009)	1.673	0.909	2.400	0.593
Shariatmadari et al (2008)	2.007	1.091	2.880	0.712

Table 8: Percentage of predicted to estimated ultimate shaft resistance factor for driven pile

Prediction	$K_{s(p)}/K_{s(e)} > 2.00$ (100%)	$0.8<K_{s(p)}/K_{s(e)}<1.2$ (±20%)	$0.6<K_{s(p)}/K_{s(e)}<1.4$ (±40%)
Bayesian Inverse	0.0%	14.3%	28.6%
Meyerhof (1976)	0.0%	7.1%	21.4%
Tan et al (2009)	33.3%	14.3%	14.3%
Shariatmadari et al (2008)	50.0%	7.1%	14.3%

Based on Table 7 and Table 8 above, Bayesian inverse method can be considered the most accurate method to predict the unit shaft resistance since the mean (1.004) is nearly equal to the unity, the standard deviation is smaller and there is no ultimate unit shaft resistance factor of driven piles that are over predicted. Meyerhof (1976) is the second most accurate method to predict the unit shaft resistance. Shariatmadari et al (2008) over predicted by 50.0%. It can be speculated that prediction by Shariatmadari et al (2008) is not reliable in this region. The prior knowledge used by Bayesian inverse method is the K_s suggested by Tan et al. (2009). The prediction error by Tan et al. (2009) is reduced by using Bayesian inverse method. This can be observe the reduction of the percentage of over predicted (from 33.3% to 0.0%), the mean (from 1.334 to 1.004) and the standard deviation (from 0.474 to 0.356).

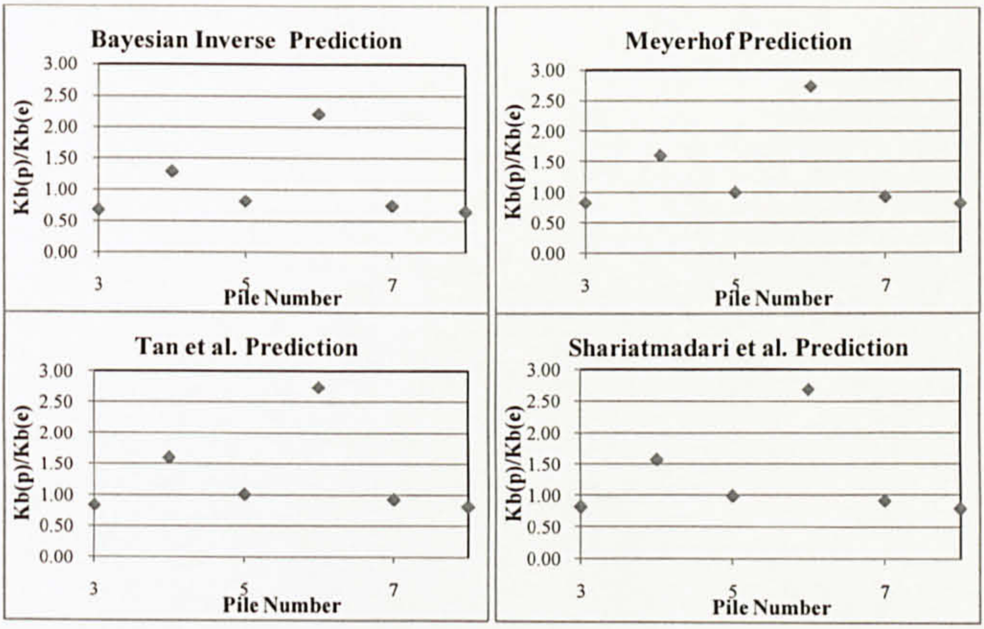

Figure 12: Ratio of predicted to estimated ultimate base resistance factor for driven pile

Table 9: Statistical comparison of predicted to estimated ultimate base resistance factor for driven pile

Prediction	Mean	Min	Max	Standard Deviation
Bayesian Inverse	1.066	0.652	2.213	0.609
Meyerhof (1976)	1.317	0.806	2.734	0.753
Tan et al (2009)	1.097	0.672	2.278	0.628
Shariatmadari et al (2008)	1.291	0.790	2.679	0.738

Table 10: Percentage of predicted to estimated ultimate base resistance factor for driven pile

Prediction	$K_{b(p)}/K_{b(e)} > 2.00$ (100%)	$0.8<K_{b(p)}/K_{b(e)}<1.2$ (±20%)	$0.6<K_{b(p)}/K_{b(e)}<1.4$ (±40%)
Bayesian Inverse	16.7%	7.1%	35.7%
Meyerhof (1976)	16.7%	28.6%	28.6%
Tan et al (2009)	16.7%	7.1%	35.7%
Shariatmadari et al (2008)	16.7%	21.4%	28.6%

In Table 9 above, Bayesian inverse method has the lowest standard deviation (0.609) and mean (1.066) almost equal to unity. However in Table 10 above, all the ultimate base resistance factors has over predicted by 16.7%. The prior knowledge used in Bayesian inverse method is the K_b suggested in (Tan et al, 2009). Bayesian inverse method slightly reduced the prediction error from (Tan et al, 2009) when compare with the mean and the standard deviation.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This paper presents the application of Bayesian inverse method to obtain the unit shaft resistance, f_s and the unit base resistance, q_b from MLT results and PDA results. The prior knowledge of bored pile and driven pile at Ara Damansara is obtained from the soil site investigation (SPT'N') and from (Tan et al, 1998; Tan et al 2009). The results were then analyzed and compared. It was found that driven pile has higher f_s and q_b than bored pile. Bayesian inverse method has proven to reduce the prediction error of the ultimate pile capacity for both bored pile and driven pile. However, further investigation should be done to confirm the reliability of the Bayesian inverse method. Time effect of the ultimate pile capacity is also required to be investigated together with the Bayesian inverse method.

Based on this limited data and other literature review, empirical equations for both bored pile and driven pile are proposed for preliminary assessment as follows;

For bored pile, f_s = 1.3 x SPT'N' $\leq$ 100 kPa. The q_b is not recommended for preliminary assessment.

For driven pile, f_s = 1.5 x SPT'N' $\leq$ 120 kPa, and q_b = 243 x SPT'N'.

CHAPTER 6

ECONOMIC BENEFITS

This project is related to the construction of foundation structures that uses bored pile or driven pile. Generally, when prediction error of a certain calculation is reduced, the cost also reduced. In this project, when the prediction error of estimating the ultimate pile capacity is reduced, the cost of the construction of foundation structures also reduced. The cost of this project is minimal since it requires two important things, the Mathematica software and the pile load test results. The major concern of this project is that Bayesian inverse method can reduce the prediction error.

Table 11: Comparison of design (f_s and q_b) and updated (f_s and q_b)

Type of pile	f_s(kPa)			q_b(kPa)		
	Design	Updated	Percentage Reduction	Design	Updated	Percentage Reduction
Bored Pile	90	58.5	35%	-	-	
Driven Pile	112.5	67.5	40%	11250	10935	3%

Based on Table 11 above, more percentage reduction means the factor of safety of designing the pile capacity can be reduce, thus reducing the cost of construction of foundation structures.

The reliability of the Bayesian inverse method and how it reduces prediction error are shown in Chapter 4: Results and Discussion (page 20 to page 25).

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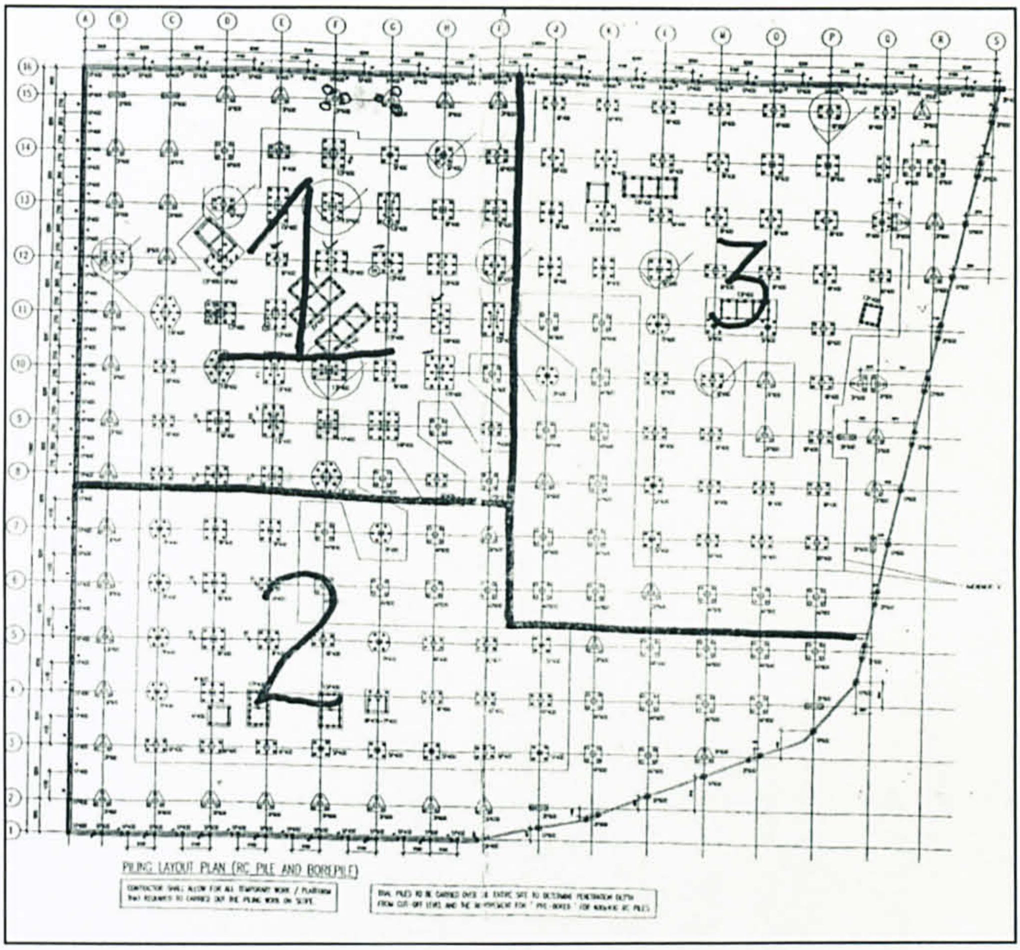
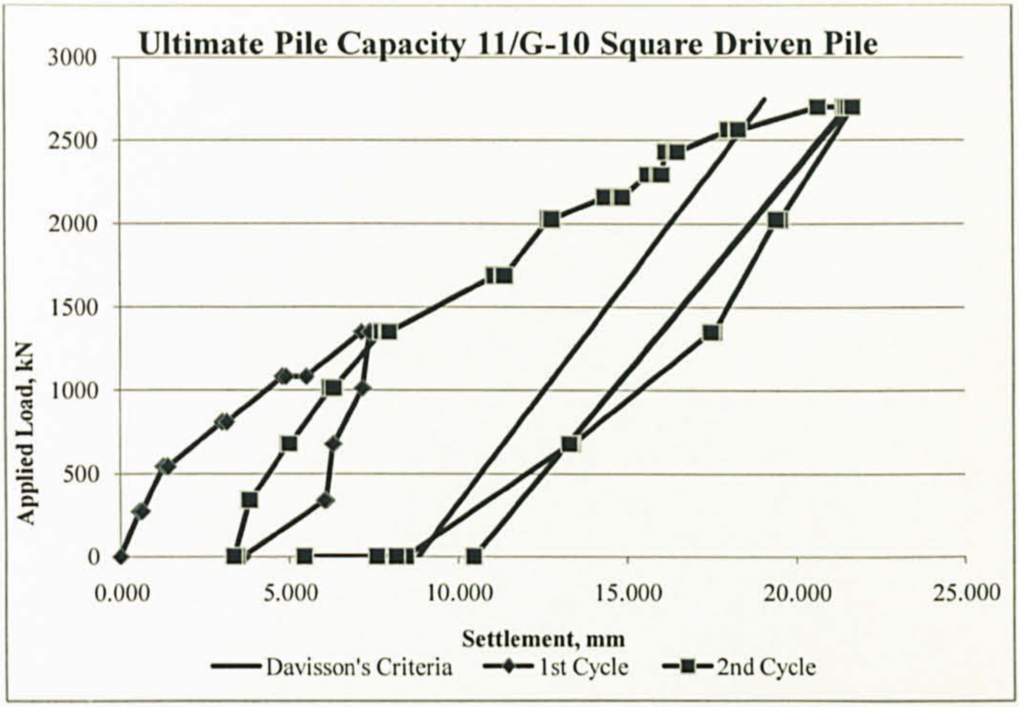
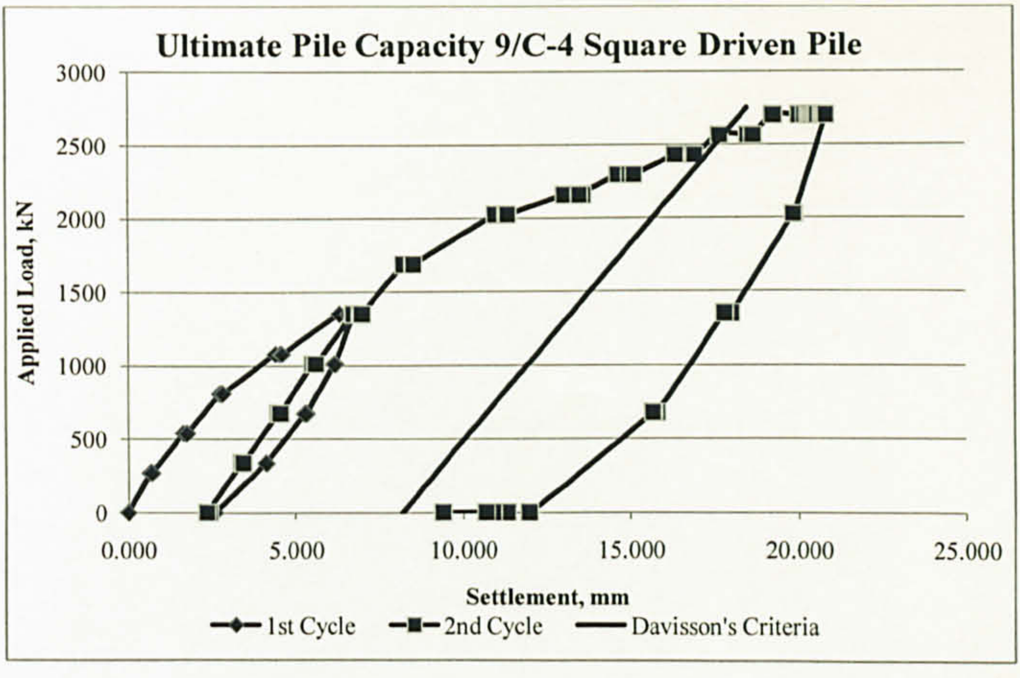
APPENDICES

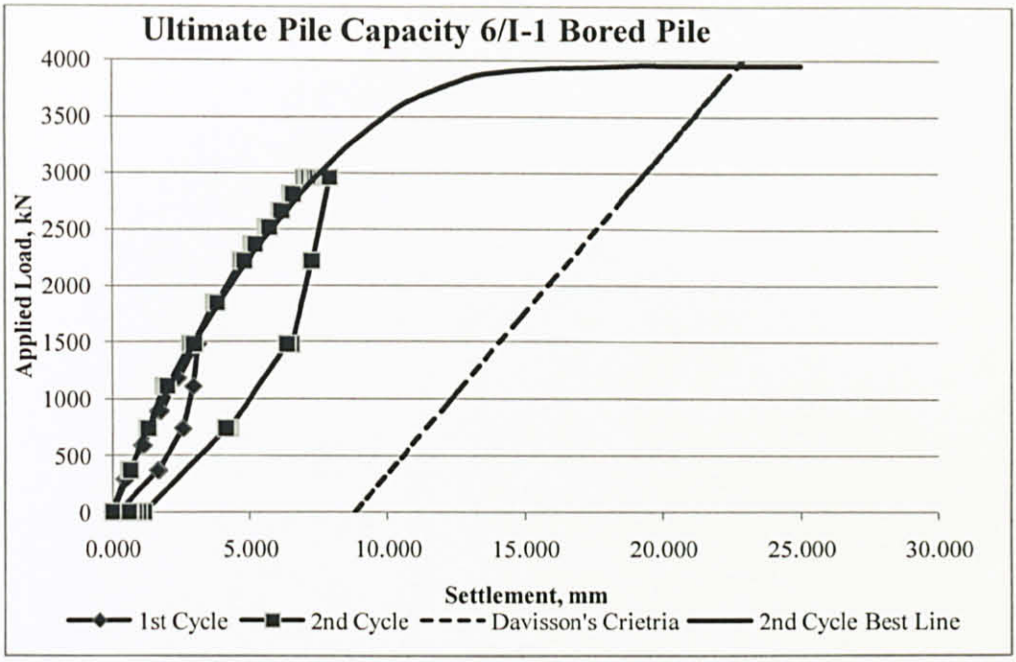
APPENDIX 1: Pile Layout Plan



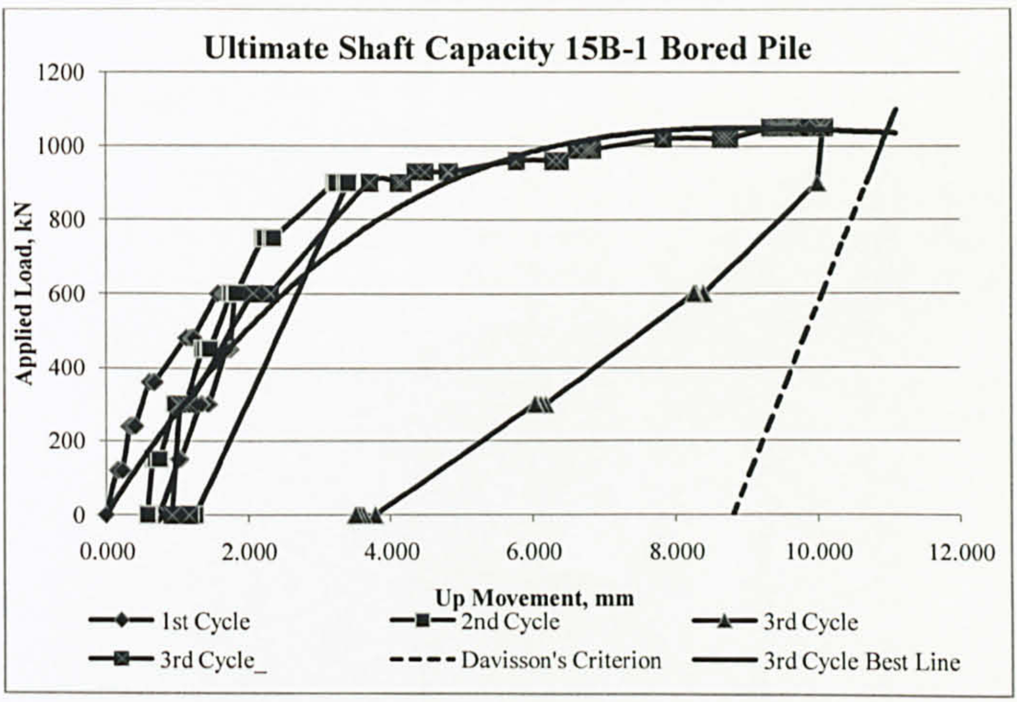
APPENDIX 2: Load Deflection Curves and Ultimate Load Determination Procedure Using Davisson's Method







Ultimate Pile Capacity 6/I-1 Bored Pile
Applied Load, kN
4000
3500
3000
2500
2000
1500
1000
500
0
0.000
5.000
10.000
15.000
20.000
25.000
30.000
Settlement, mm
1st Cycle
2nd Cycle
Davisson's Crietria
2nd Cycle Best Line



Ultimate Shaft Capacity 15B-1 Bored Pile
Applied Load, kN
1200
1000
800
600
400
200
0
0.000
2.000
4.000
6.000
8.000
10.000
12.000
Up Movement, mm
1st Cycle
2nd Cycle
3rd Cycle
3rd Cycle_
Davisson's Criterion
3rd Cycle Best Line

APPENDIX 6: Bore Hole Log