EFFECTS OF BENTONITE ON SKIN FRICTION OF BORED PILES

SUAN TEE HOOI

CIVIL ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
JUNE 2010

EFFECTS OF BENTONITE ON SKIN FRICTION OF BORED PILES

by

Suan Tee Hooi

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

JUNE 2010

Supervisor:
Dr Indra Sati Hamonangan Harahap

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

EFFECTS OF BENTONITE ON SKIN FRICTION OF BORED PILES

by

Suan Tee Hooi

A project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Civil Engineering)

Approved:

____

Dr Indra Sati Hamonangan Harahap
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

January 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.

____

Suan Tee Hooi

ABSTRACT

Bored piles are commonly used to support heavily loaded structures in Malaysia. Bored piles transfer the applied loads to the ground via skin friction of pile shaft and end bearing of pile toe. During excavation of borehole, bentonite is sometimes used to support the wall of the borehole or to avoid soil collapse in the borehole. This report studies the effects of bentonite on the skin friction of bored piles. Static load tests were conducted on five bored piles located on Kuala Lumpur Kenny Hill Formation, where three of them were constructed with bentonite and the rest of them without. The ultimate pile capacity of each pile is obtained from the load-settlement curves using Davisson's method. The actual field parameters such as skin friction and end bearing resistance are then back-calculated using probabilistic inverse method. Comparison is done between the parameters of bored piles constructed with and without bentonite. The result shows a smaller value of skin friction for bored piles constructed with bentonite compared to the bored piles constructed without bentonite.

ACKNOWLEDGEMENT

I would like to express deepest appreciation to all those who gave me the possibility to complete my Final Year Project.

First of all, I would like to thank my Supervisor, Associate Professor Dr. Indra Sati Hamonangan Harahap for his guidance to the completion of this project. His vast knowledge especially in Geotechnical Engineering field is definitely helpful in the completion of my Final Year Project.

I would like to extend my gratitude to my ex-colleagues in Web Structures (M) Sdn. Bhd, Ms Christine Yong, for her willingness to provide the information regarding my project; as well as Mr. Goh Choon Kai, for giving constructive advice and sharing his industrial experiences. Besides that, Mr. Amirhossien Hamedzadeh has also offered his help in solving problems I encountered while working with Mathematica 6.0 software which I am really grateful of.

In addition, a thank you to all the lecturers and staff of UTP Civil Engineering Department for their generosity in offering help whenever I need them. Along the way, I would also like to thank Ms Kareen Lee, for her patience in answering my questions and doubts regarding data analysis. She has also shared her experiences in the completion of her Final Year Project.

Lastly, many thanks to all my friends and coursemates, for their physically and mentally supports in accomplishment of this project.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

BACKGROUND

In Malaysia, bored piles are commonly used as foundation to support heavy structures such as high-rise buildings and bridges. This is due to its high capacity, low noise, low vibration and flexibility of sizes to suit different loading and subsoil conditions. Bored piles are also favored in residual soil, where there are difficulties for driven piles to penetrate into hard soil layer or boulders. Bentonite is commonly used as drilling mud in geotechnical engineering industry due to its unique rheological properties. It is used to prevent soil collapse during borehole excavation.

This report studies a high-rise project at Jalan Pinang, Kuala Lumpur which located on Kuala Lumpur Kenny Hill Formation. Bored piles with length up to 46m were used as the foundation of the building. All the bored piles were designed using SPT-N values obtained from Standard Penetration Test conducted prior to construction of bored piles. Three preliminary test piles were load tested to prove the parameters used during design. All the three test piles and one working pile were constructed using wet method with bentonite as the stabilizing fluid while the rest of the working piles were constructed without bentonite.

PROBLEM STATEMENT

In this project, bentonite was used in a few bored piles during drilling stage. Bentonite has the tendency to form a layer of filter cake on the soil surface which is slippery and has low permeability. This will affect the properties of the soil around the shaft surface of bored piles and thus reduce the skin friction of bored piles. Thus, a longer pile would be needed to gain enough skin friction to support the applied load. Hence, use of bentonite in bored pile construction would not be cost-effective.

Pile load tests were conducted on the preliminary test piles and a few selected working piles. The actual field parameters are back calculated from pile load tests to be used to compare between bored piles constructed with and without bentonite. In this project, attempts have been made to prove the reduction of skin friction pile shaft in the presence of bentonite during bored piles construction.

OBJECTIVES

The objective of this project is to determine the effects of bentonite on skin friction of bored piles.

SCOPE OF STUDY

The main focus of this project is to study the effects of bentonite in skin friction of bored pile, particularly on Kuala Lumpur Kenny Hill formation.

The scope of this study covers the following:

- Bored pile design capacity calculation
- Ultimate load capacity calculation
- Back calculation of field parameters from pile load tests
- Comparison of skin friction of bored piles constructed with and without bentonite

CHAPTER 2

LITERATURE REVIEW

A foundation with depth more than 15m below the ground surface is regarded as deep foundation. Drilled shaft is large diameter bored piles commonly used as foundation especially for heavily loaded structure. These foundations transfer applied loads to the ground, meanwhile achieving design capacity via two mechanisms: skin friction and end bearing. The skin friction is the result of sliding friction along the side of the pile shaft and adhesion between the soil and the shaft while end bearing is the result of compressive loading between the bottom of the bored piles and the soil.

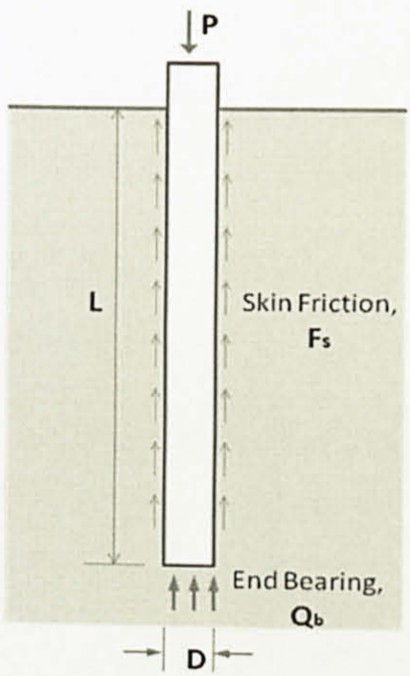


Figure 1: Load transfer mechanisms of bored piles

In Malaysia, construction of bored holes typically involves excavation of boreholes and casting of concrete in the hole. In some cases where water table is high, the borehole may become 'wet' because of the inflow of water. In such cases, lining tubes or casings are often used to support the sides of boreholes to avoid soil collapse into the boreholes as it may result in accumulations of loose soil at pile toe or discontinuities in the shaft. Casings may be avoided by providing support to the borehole in the slurry form of bentonite clay. For wet borehole, casting of concrete is usually carried out by using tremie method. A watertight segmental tremie pipe is lower to the bottom of borehole allowing ground water or bentonite slurry to be displaced by rising concrete. The tremie pipe bottom end should remain submerged in concrete with an adequate margin of safety.

Bentonite has very unique rheological properties, in which it suspends in water to form a viscous, shear thinning material at low concentration of water. For these reasons, bentonite is often used to support the wall of borehole. However, bentonite tends to form a slippery and low permeability filter cake on the wall of boreholes. Research previously done indicates that bentonite will affect the properties of soil and thus the skin friction of bored piles.

According to Tomlinson & Woodward, softening of the clay will occur if bentonite is used to support the sides of the borehole, this will then affect the pile shaft. Reese *et al.* also describe that an appropriate reduction in end bearing resistance should be allowed in case of any entrapment of bentonite slurry beneath the pile-base.

Fleming and Sliwinski reported no difference in the adhesion factor between bored piles drilled into clays in bentonite-filed holes and dry holes. Tomlinson and Woodward (2008) pointed out that if the use of a Bentonite slurry to support an unlined hole in clay does not reduce the shaft friction, this must mean that the rising concrete placed by tremie pipe beneath the slurry has the effect of sweeping the slurry completely off the wall of the borehole. It is difficult to conceive that this happen in all cases; therefore it is recommended that an adhesion factor α for London Clay, or for other clays, should be reduced by 0.8 to allow for the use of bentonite unless a higher value can be demonstrated by loading test. In clays other than London Clay, there is no information from loading tests or publications, the pile capacity should be confirmed by field loading tests(1).

Ng (2002) reported that the formation of low shear strength material, filter cake, on the wall of excavation trench would have adverse effect on shaft resistance capacity. He summarized that majority researcher results show that the ultimate shaft resistance would be reduced up to 20% with the present of bentonite suspension and suggested that the cohesion of the bentonite filter-cake at the pile interface was rapidly mobilized at low displacement. Weiss (1965) carried out direct shear tests on concrete slabs cast horizontally on compacted sands and found that the concrete / sand interface coated with bentonite resulting a slightly reduction of shaft resistance.

Kraft and Lyons (1974) have shown that the adhesion factor used to calculate the shaft friction on the grout or clay interface is of the same order as that used for design of conventional bored and cast-in-place concrete piles. Where bentonite is used as the drilling fluid a reduction factor should be adopted.

Pile load tests are often carried out to obtain actual soil parameters to be used either in designing pile capacity or proving working assumption during design stage. However, load settlement curves from the pile load tests do not always indicate the ultimate pile capacity, or the load required to cause failure. Furthermore, the load tests are usually carried out in bored piles with different geometry with plenty of uncertainties, therefore, it is hard to conclude anything out of the load-settlement curves alone. Harahap and Wong (2008) presented a method to interpret pile load tests to obtain probabilistic characteristics of ultimate load. Soil parameters such as skin friction and end bearing can be extracted from their joint probability distribution using probabilistic inverse analysis method.

CHAPTER 3

METHODOLOGY

PROJECT SITE LOCATION AND GEOLOGY

The project site is located at Jalan Pinang, Kuala Lumpur. The site is sitting on Kuala Lumpur Kenny Hill Formation.

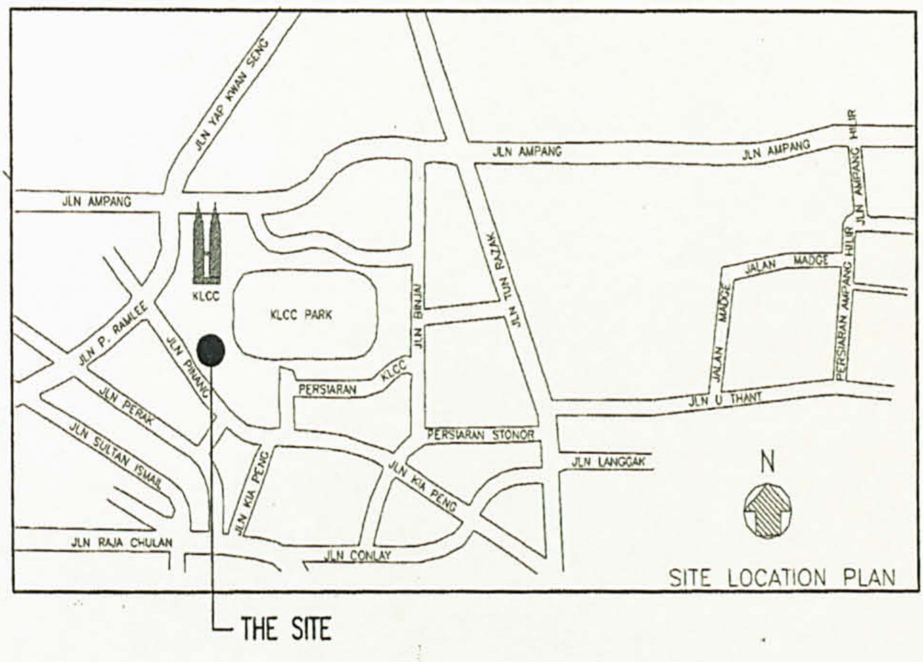


Figure 2: Project Site Location

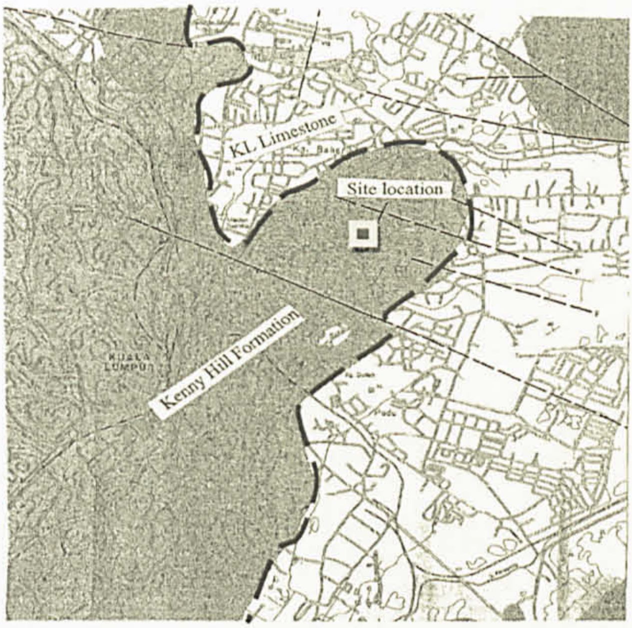


Figure 3: Project Site Geology

SOIL CONDITIONS AND TEST PILES DETAILS

This research is based on a high-rise project in Kuala Lumpur, Malaysia. The site is located on the Kenny Hill Formation of Upper Palaeozoic age and is overlying the Kuala Lumpur Limestone, which mainly consists of stiff to hard clayey silt, and silty clay with sand or gravel. In between of these materials are layers of medium dense to very dense clayey and silty sand and gravel. The ground water levels were generally at about 6m below the existing ground surface. Within the termination depth of 70m, limestone formation was not encountered. In general, the hard soil stratum can be encountered at about 9m to 12m below ground surface with SPT-N value of more than 50.

All the test piles were installed after a cut-off level of between 10m to 14m from ground (≈R.L.37m). Prior to the commencement of boring, a temporary casing of 7m long was installed. For the piles constructed with wet method, Bentonite was used as the stabilizing fluid to support the wall of the holes during the boring stage. While for piles constructed with dry method, a temporary 7m long casing was installed for the purpose of debonding above cut-off level. When the design bored pile depth was reached, a mechanical bucket was used to remove the loose materials at the base. Concrete grade 35 was placed using the tremie pipe method. The test pile details are shown in the following table:

Table 1: Test Piles Details

Bored Pile	Diameter (mm)	Length (m)	Working Load (kN)	Remarks
PTP 1	1000	14.18	6800	With bentonite
PTP 2	1200	16.42	10000	With bentonite
BP27	1200	23.00	10000	With bentonite
BP 85	1000	19.50	6800	Without bentonite
BP 62	1500	29.00	16000	Without bentonite

DESIGN OF BORED PILES

The ultimate pile load, Q_u is calculated using the following equation:

$$Q_u = Q_s + Q_b \quad [1]$$

Where

Q_b = Load carried at the pile tip

Q_s = Load carried by skin friction developed at the side of the pile (caused by shearing resistance between the soil and the pile shaft)

For safety purposes, the pile capacity depends mainly on the shaft friction with little contribution of end bearing. Ultimate skin friction, Q_s is given by the formula:

$$Q_s = \sum_i (f_s \times A_s) \quad [2]$$

Where

f_s = Unit skin friction for each layer of embedded soil

A_s = Pile shaft area

The end bearing is only considered at the pile toe. Ultimate end bearing, Q_b is given by the formula:

$$Q_b = f_b \times A_b \qquad [3]$$

Where

f_b = End bearing pressure at pile tip

A_b = Cross-sectional area of pile toe

Substituting equation [2] and [3] into [1],

$$Q_u = (f_s \times A_s) + (f_b \times A_b) \qquad [4]$$

Since bored piles are generally constructed in tropical residual soils which have complex soil characteristics, current theoretically based formula may not be necessary in design of bored pile geotechnical capacity. The complexity of these founding medium with significant changes in ground properties over short distance and friable nature of the materials make undisturbed sampling and laboratory strength and stiffness testing of the material difficult. Furthermore, the effect of soil disturbance, stress relief and partial reestablishment of ground stresses that occur during the construction of bored pile are not considered in the formulas *(Tan and Chow, 2003).*

Semi-empirical method is used for the calculation of geotechnical capacity of bored piles, which skin friction and end bearing of bored piles are related to SPT'N values. In the correlations established, the SPT'N' values generally refer to uncorrected valued before pile installation.

The commonly used correlations for bored piles are as follows:

$f_s = K_s \times SPT'N\ (in\ kPa)$

$f_b = K_b \times SPT'N\ (in\ kPa)$

Where:

K_s = Ultimate skin friction factor

K_b = Ultimate end bearing factor

SPT'N' = Standard Penetration Tests blow counts (blows/300mm)

For skin friction, value suggested by Chang & Broms is adopted, which K_s is 2 for bored piles in residual soils with SPT (N)<150. In other words, f_s=2×SPT (N) is adopted. For end bearing, K_b value used in calculation of bored pile capacity is 30 with maximum end bearing capacity f_b of 4000kN/m^2.

The factor of safety (FOS) used in static evaluation of bored pile geotechnical capacity are partially FOS on shaft (F_s) and base (F_b) respectively; and global FOS (F_g) on total capacity. However, for this project, the allowable geotechnical capacity, Q_{all} adopted is

$$Q_{all} = \frac{Q_s + Q_b}{F_g}$$

Where:

Q_s = Ultimate shaft capacity

Q_b = Ultimate base capacity

For this project, the safety factor, F_g = 2.5 was adopted.

Design F_s and Q_b of bored piles

During pile design stage, shaft frictional resistance of bored piles was calculated by semi-empirical method using N values from Standard Penetration Tests (SPT) of the nearest borehole. The skin friction, F_s is calculated based on the soil layers along the pile shaft and an average value is determined for each pile. The end bearing of pile is calculated based on SPT'N value of the soil on the pile toe. Design calculation of the bored piles is shown in Appendix D. The average values of F_s and Q_b for the test piles are summarized in the table below:

Table 2: Design F_s and Q_b of Test Piles

Pile No.	Cut-off Level Below Ground (m)	Pile Toe Level Below Ground (m)	Average Skin Friction, F_s (kPa)	End Bearing, Q_b (kN)
PTP 1	13.82	28	235.8	3141.6
PTP 2	13.14	29.56	271.2	4523.9
BP 27	12.567	35.567	265.5	4523.9
BP 85	10.729	30.229	242.0	2356.2
BP 62	13.873	42.873	263.8	6441.2

The skin friction factor, K_{su} used for design of the piles is 2; whereas the end bearing factor, K_{bu} used is 30. These design values of F_s will be counter-checked with the back-calculated values of F_s to observe the correlation of both.

PILE LOAD TESTS

The pile loading test conducted was static load test. The instrumented test piles were cast-in-situ reinforced concrete piles with nominal diameters vary from 900mm to 1500mm. Pile lengths were different depending on pile diameter and design capacity.

PTP1 and PTP2 are preliminary test piles. The rest of the test piles are working piles, the maximum applied loads for working piles were only up to 1.5 times the design working load.

The instrumented test piles were tested by normal Maintained Load (ML) Method, using reaction piles system. Tell-tale extensometers were installed internally in the test pile to monitor the strain development of the pile during testing. For PTP 1 and PTP 2, Vibrating Wire Strain Gauges (VWSGs) were installed at several levels on the pile with 4 numbers of them per level. To monitor the pile movement, the tell-tale extensometers were monitored using Linear Variation Displacement Transducers (LVDTs) mounted to the pile top and reference frame. The loads were applied on the piles in 2 to 3 cycles.

PILE LOAD TEST RESULT

The load movement behavior of the pile was assessed in each loading cycles and the results were shown in load-settlement graph. The load distribution curves indicating load distribution along the shaft and at the base were derived from computations based on the measure changes in strain gauge readings and estimated pile properties such as steel content, cross-sectional areas and modulus of elasticity.

Load transferred (P) at each level is calculated as follows:

$$P = \epsilon \left(E_c \times A_c + E_s \times A_s \right)$$

Where

ϵ = average change in strain gauge readings

A_c = cross-sectional area of concrete

E_c = Concrete Modulus

A_s = cross-sectional area of steel reinforcement bars

E_s = Young Modulus of Elasticity in steel = 200kN/mm^2

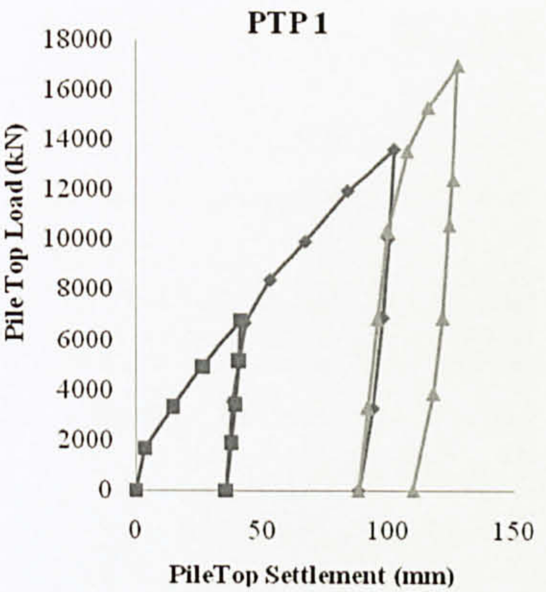


Figure 4: Load-settlement behavior of PTP 1

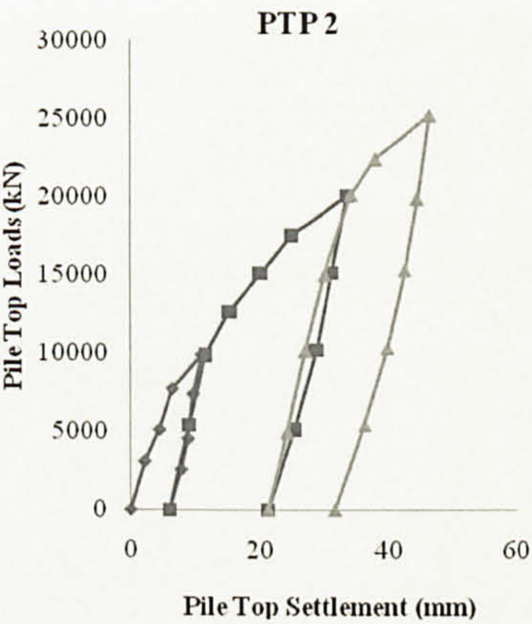


Figure 5: Load-settlement behavior of PTP 2

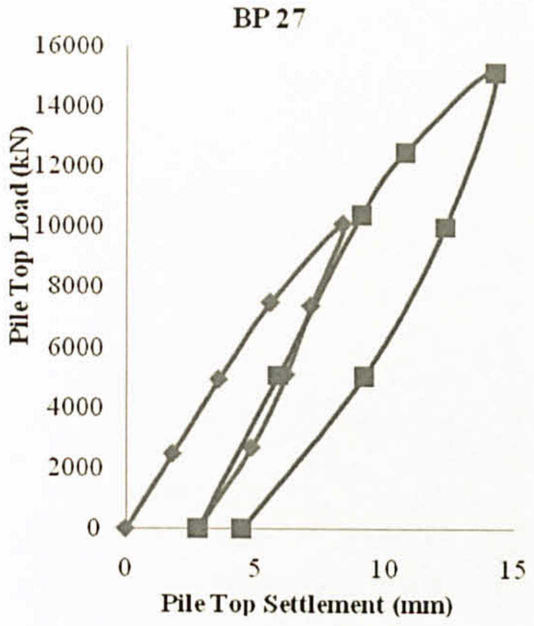


Figure 6: Load-settlement behavior of BP 27

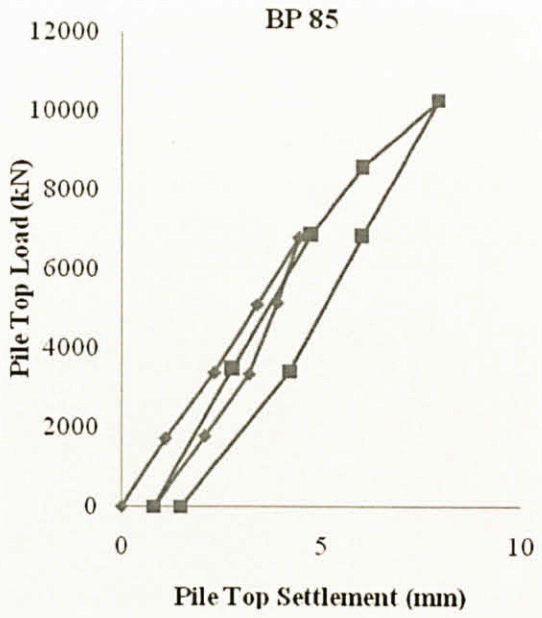


Figure 7: Load-settlement behavior of BP 85

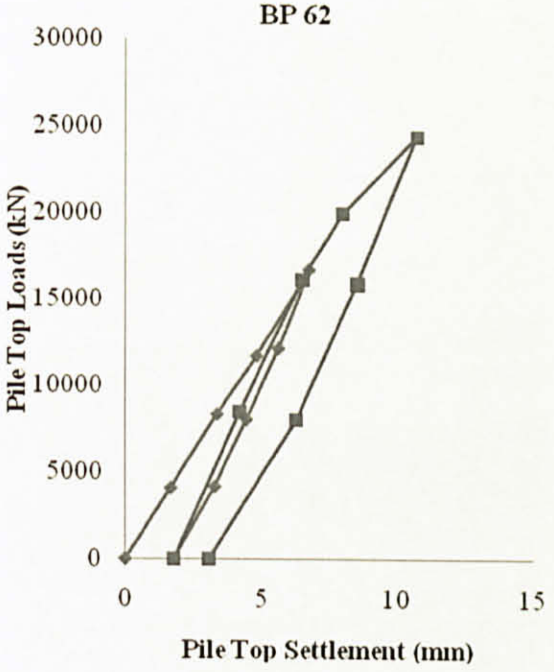


Figure 8: Load-settlement behavior of BP 62

Figure 4 to 8 show the load settlement curves for PTP1, PTP2, BP27, BP85 and BP62 respectively. PTP 1 was tested to failure with the maximum applied load of 16984kN and the pile top had settled by 127.8mm. PTP 2 was a preliminary test pile and was tested up to 2.5 times the design load. The maximum settlement on the pile top of PTP2 was 46.53mm. Like PTP1 and PTP2, BP27 is also constructed with bentonite, however, it was only tested to 1.5 times the working load. BP27 had settled 14.28mm at the pile top.

BP85 and BP62 are the working piles constructed without bentonite. The maximum applied load for BP85 and BP62 were 10281kN and 24332kN respectively. Pile top of BP85 had settled 7.91mm while for BP62, 10.72mm.

The load distribution curves for PTP 1 and PTP2 shown in the Figure 9 and Figure 10 were derived from computations based on the measured changes in strain gauges readings and the pile properties. The load P at each level was calculated using the equation $P = e(E_cA_c + E_sA_s)$ where e is the average change in the VWSG readings, A_c and A_s are the cross-sectional areas of concrete and steel respectively; E_c and E_s are the elastic modulus of concrete and steel respectively.

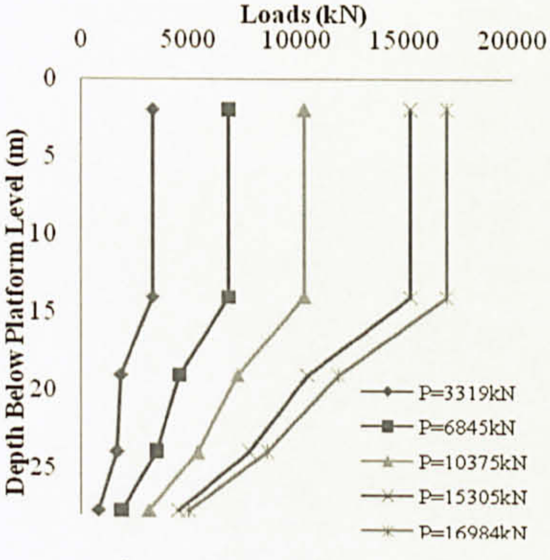


Figure 9: Load distribution curves for PTP 1

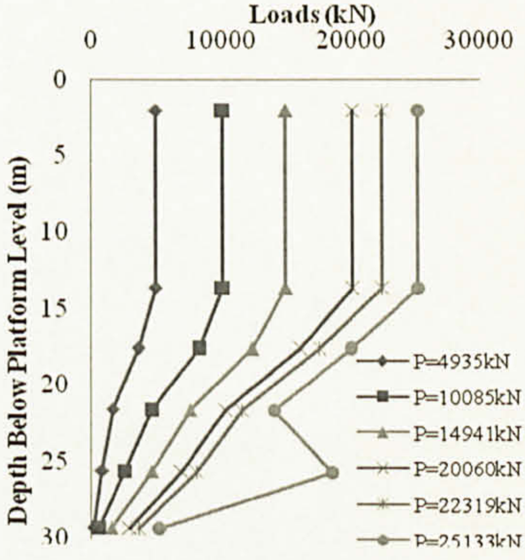


Figure 10: Load distribution curves for PTP 2

Davisson's (1973) method was used to determine the ultimate load capacity from the load-settlement curves. This method defines that the ultimate capacity occurs at a settlement of 4mm+B/120+PL/(AE). PTP 1 and PTP 2 were tested to fail, therefore only these two piles gave ultimate load based on Davisson's method. Figures below show ultimate pile capacity using Davisson's criterion.

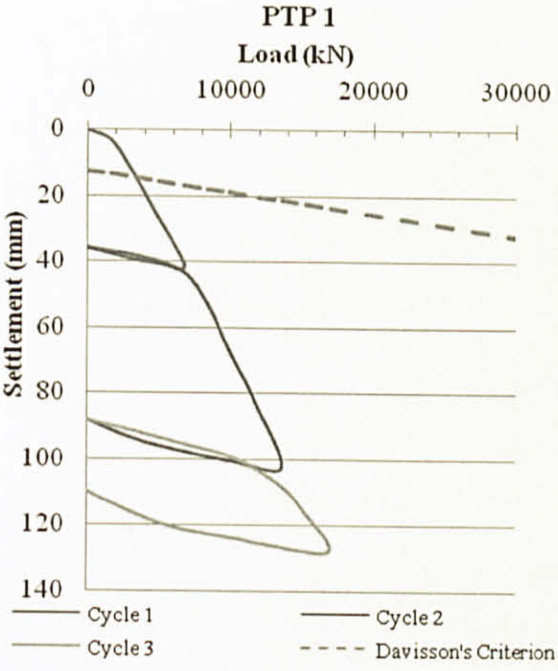


Figure 11: Davisson's criteria for PTP 1

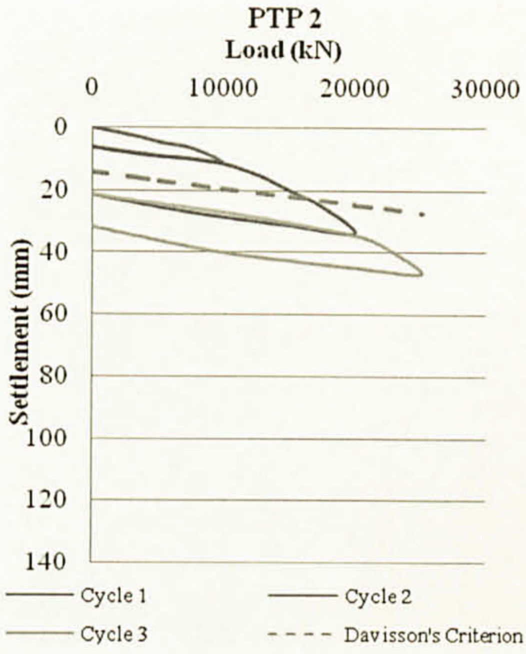


Figure 12: Davisson's criteria for PTP 2

For the rest of the bored piles which were not tested to fail, the load settlement curves were extrapolated to meet Davisson's criteria to obtain the estimated ultimate capacities. The following table shows the ultimate capacities from static load tests:

Table 3: Static load test results

Pile No.	Diameter (mm)	Pile Length (m)	Ultimate Capacity, Q_u (kN)	Estimated Q_u By Extrapolation (kN)
PTP 1	1000	14.18	3400	-
PTP 2	1200	16.42	16500	-
BP 27	1200	23.00	Not Fail	22000
BP 62	1500	29.00	Not Fail	41500
BP 85	1000	19.50	Not Fail	24200

BACK-CALCULATION OF FIELD PARAMETERS

The data gathered from pile load tests were categorized according to presence of bentonite in bored pile construction, e.g. Case 1 is the bored piles constructed with bentonite and Case 2 is the bored piles constructed without bentonite. The pile load tests were interpreted using Bayesian interpretation using following steps:

1) The model space is $m = (f_S, Q_b)$, where f_s is skin friction and Q_b is end bearing of bored piles.
2) The probability density model to describe experimental uncertainty, $\rho_D(\mathbf{d}) = k\exp\left(-\frac{1}{2}\sum\left(\frac{d^i - d^i_{obs}}{\sigma^i}\right)^2\right)$ is formed using the theoretical model $d=f(m)$ as in equation [4], and d_{obs} is ultimate pile capacity.

3) The prior knowledge can be incorporated in $\rho_M(m) = \rho_M(f_S, Q_b)$. In this case, only the effect of skin friction and end bearing resistance are considered.

4) The joint probability density function is $\sigma_M(f_s, Q_b) = \int_{-\infty}^{\infty}\sigma_M(f_S, Q_b)df_S$.

The posterior joint probability density for Case 1 and Case 2 were plotted in a contour plot for comparison purposes.

ADDITIONAL BORED PILES FROM ADJACENT SITE

An additional analysis was carried out for two bored piles at a project site at Jalan Binjai, Kuala Lumpur, which is around 1km from Jalan Pinang, Kuala Lumpur. The locations of both sites are depicted in the Figure 13.

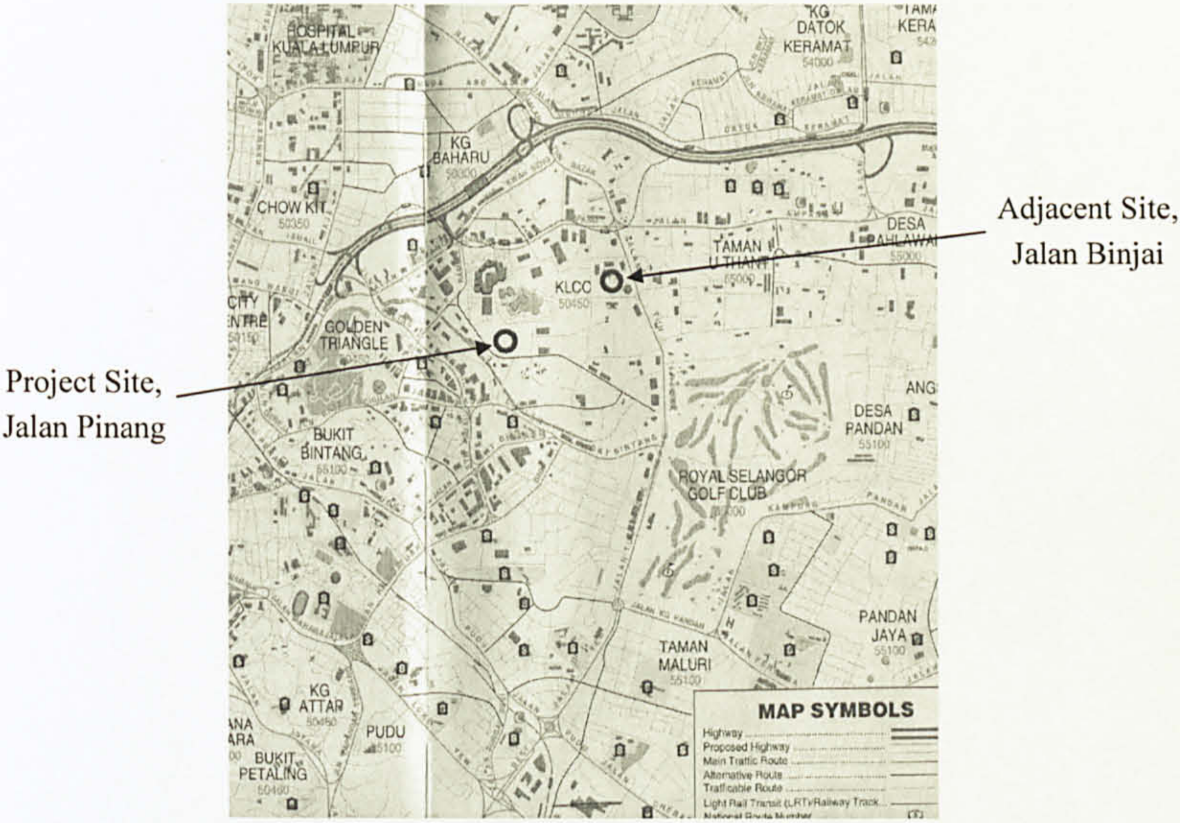


Figure 13: Location of project site and adjacent site

This adjacent project site is also located on Kenny Hill formation. Static load test was conducted on the two selected bored piles using the same method as discussed previously. The bored piles details are as follow:

Table 4: Test Pile Details of Adjacent Site

	PTP2	BP120
Diameter (mm)	900	1000
Length (m)	25	25.5
Working Load (kN)	5500	9800
Average F_s (kPa)	232	300
Q_b (kN)	2545	3141.6

The load settlement curves of the bored piles are as follow:

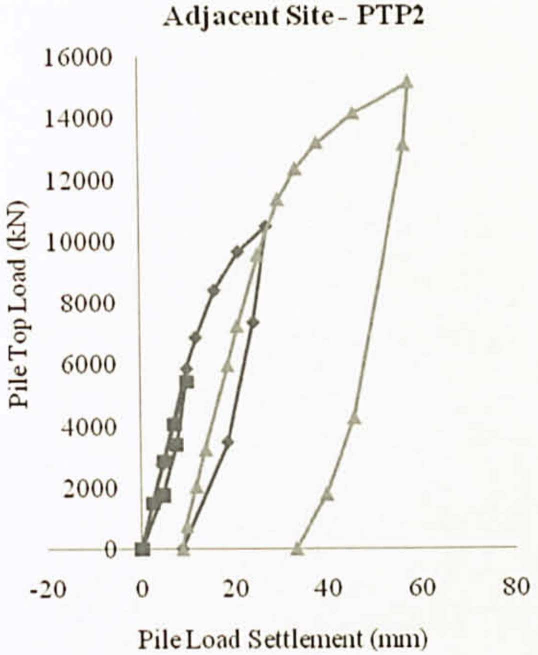


Figure 14: Load settlement curve of PTP 2 at adjacent site

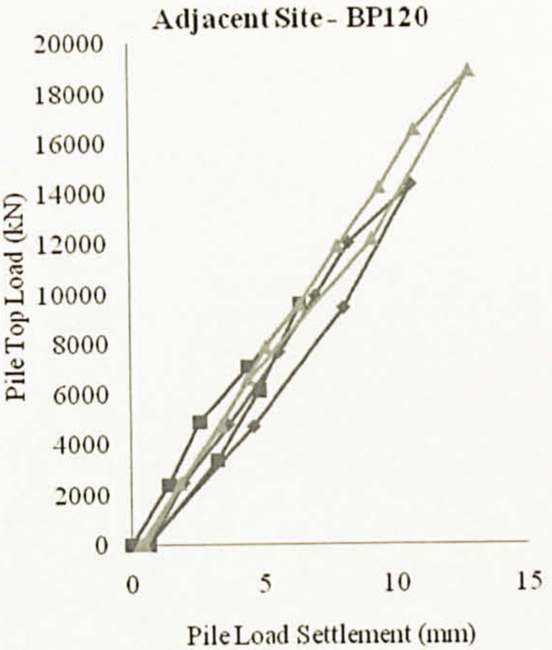


Figure 15: Load settlement curve of BP120 at adjacent site

From the figures shown above, both PTP2 and BP120 were loaded with three cycles. PTP2 is a preliminary test pile, it was tested up to three times the working load or to failure. The maximum applied load of PTP2 was 15144kN and its pile top settled 54.09mm. BP120 was loaded up to 18890kN with maximum settlement 12.91mm.

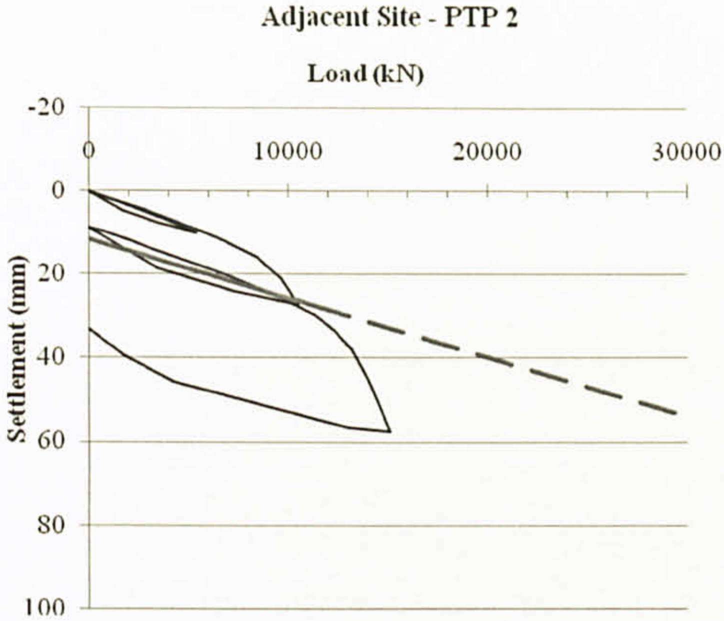


Figure 16: Davisson's criteria for PTP 2

Ultimate load capacities of both PTP 2 and BP120 were determined using Davisson's criteria. However, only PTP2 was tested to failure, therefore the ultimate capacity is 10300kN using Davisson's criteria. Ultimate load for BP120 was estimated by extrapolation of load settlement curve to meet the Davisson's criteria at 36000kN.

The additional information of the bored piles from Jalan Binjai site will be used to back-calculate the skin friction of the broed piles. The results will then be compared with the results obtained from the project site at Jalan Pinang.

CHAPTER 4

RESULTS AND DISCUSSION

COMPARISON BETWEEN BORED PILES CONSTRUCTED WITH AND WITHOUT BENTONITE

The probability inverse analysis was carried out in two separated cases: case 1 is for the bored piles constructed with bentonite and case 2 is for the bored piles constructed without presence of bentonite. In this analysis, pile geometry and ultimate pile capacity are the known variables used to back-calculate the skin friction, F_s and end bearing, Q_b of the piles. The contour plots of joint probability density of both cases are presented below:

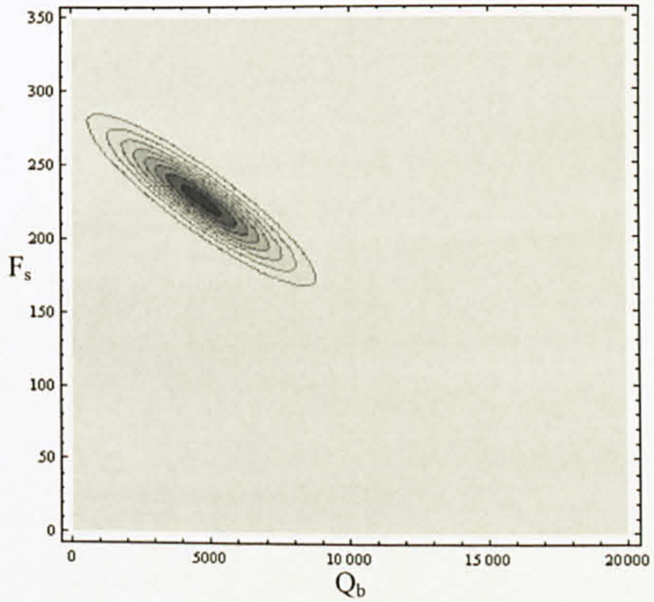


Figure 17: Posterior joint probability density of bored piles with bentonite

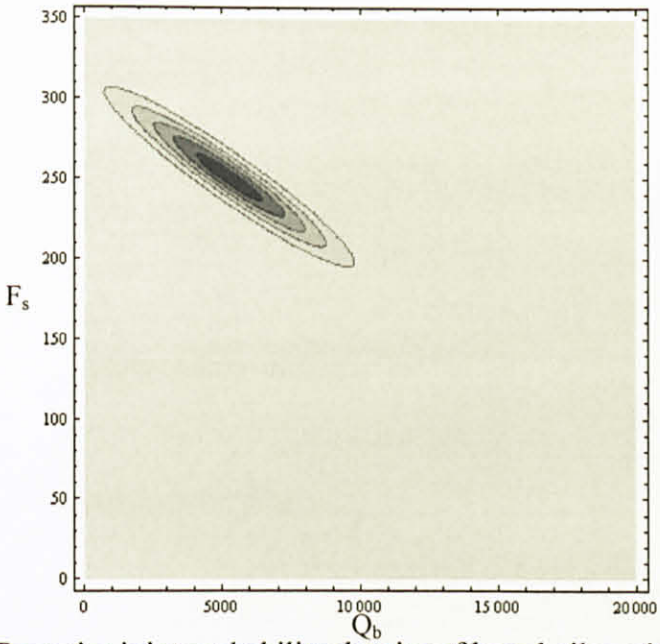


Figure 18: Posterior joint probability density of bored piles without bentonite

The colour intensity of the contour indicates the probability of skin friction and end bearing respectively. The higher the intensity, the higher probability is the value of parameters.

An integration of skin friction and end bearing with respect to each other were also done to obtain the maximum value or the value with highest probability, the results are as follow:

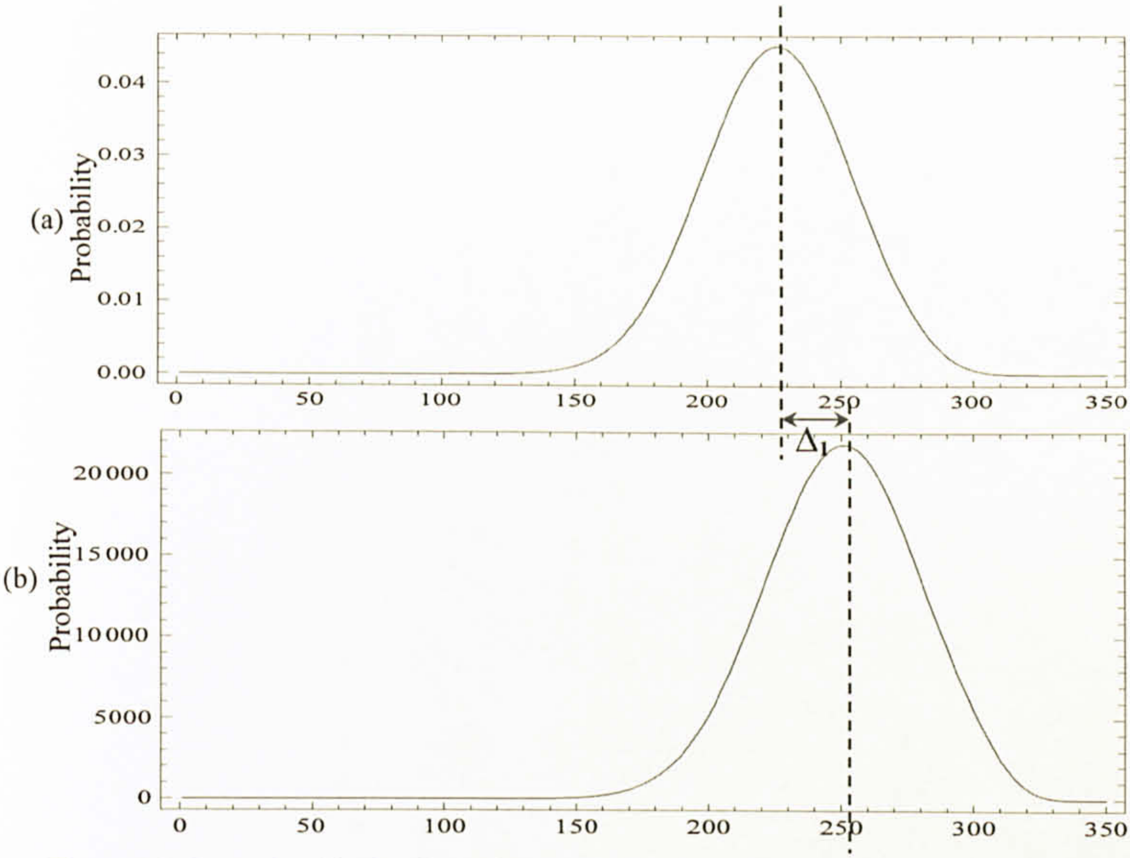


Figure 19: Posterior distribution of unit skin friction of bored piles (a) with bentonite and (b) without bentonite

Figure 19 shows the integration of skin friction of pile shaft with respect to end bearing resistance of the bored piles. Figure 19(a) shows the probability of skin friction of the bored piles constructed with bentonite and Figure 19(b) shows the probability of skin friction for bored piles constructed without bentonite. The peaks of the graphs indicate the highest probability of the parameter. As indicated, the peak of Figure 19(a) is at a value smaller than the peak of Figure 19(b). The difference of the peaks of both graphs is denoted as Δ_1. It is clearly shown that the bored piles constructed without bentonite have higher skin friction compared the ones with bentonite.

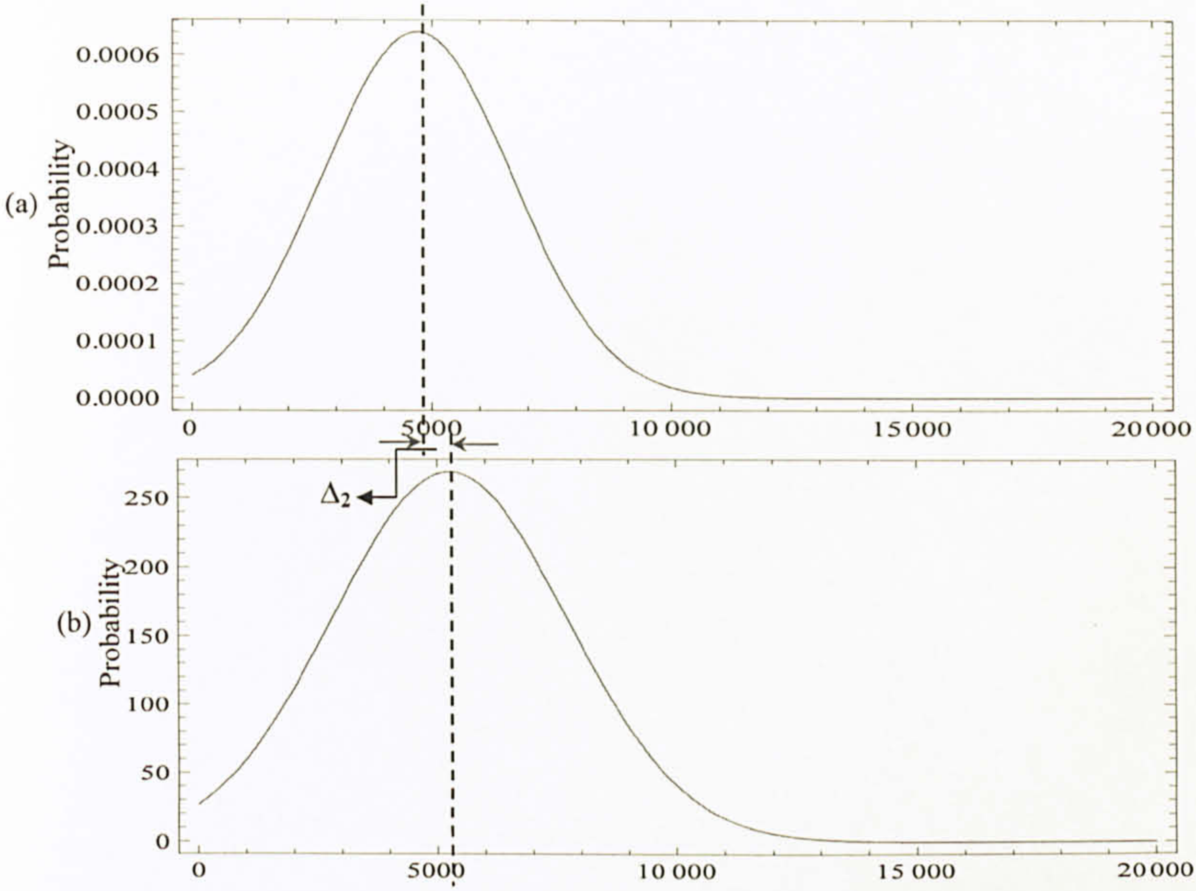


Figure 20: Posterior distribution of unit end bearing of bored piles (a) with bentonite and (b) without bentonite

Figure above shows the integration of end bearing resistance of pile toe with respect to skin friction of pile shaft. Figure 20(a) shows the probability of end bearing for bored piles constructed with bentonite while Figure 20(b) shows the probability of end bearing for bored piles constructed without bentonite. The peak of Figure 20(b) is observed to have shifted slightly to the right compared to Figure 20(a). The difference between the peaks of both graphs is denoted as Δ_2. There is a slight decrease in the unit end bearing for bored piles constructed with bentonite compared to the one constructed without.

The comparison of back-calculated field parameters is summarized in the table below:

Table 5: Comparison of bored piles with and without bentonite

	With Bentonite	**Without Bentonite**
Pile Ref. No.	PTP 2	BP 62
Pile Diameter (mm)	1200	1500
Pile Length (m)	16.42	29.00
Ultimate Capacity (kN)	16500	41500
Skin Friction, F_s (kPa)	227	253
End Bearing, Q_b (kN)	4850	5100

It is observed that for bored piles constructed with the presence of bentonite has lower skin friction compared to the bored piles constructed without bentonite. The percentage difference of skin friction between both cases is approximately 10.3%. While for the case of end bearing, Q_b of the bored piles constructed without bentonite is slightly higher than the piles constructed without bentonite. The percentage difference for end bearing is 5%.

The results obtained have proven that the bentonite filter cake formed is not swept completely off the wall of borehole by the rising concrete placed by tremie pipe. The slippery filter cake will affect the pile shaft which will then reduce the skin friction of the bored pile. The result shows that the skin friction of bored piles constructed with bentonite has reduced approximately 11%, this is quite close with the value suggested by Ng (2002) which is a 20% reduction in pile skin friction with the presence of bentonite suspension. From the result, it is observed that there is also possibility of entrapment of bentonite slurry beneath the pile-base, therefore a reduction of 5% on the pile end bearing capacity.

COMPARISON OF BORED PILES FROM ADJACENT SITE

The probability inverse analysis was carried out on two bored piles at the adjacent site. Below is the joint probability density of the bored piles.

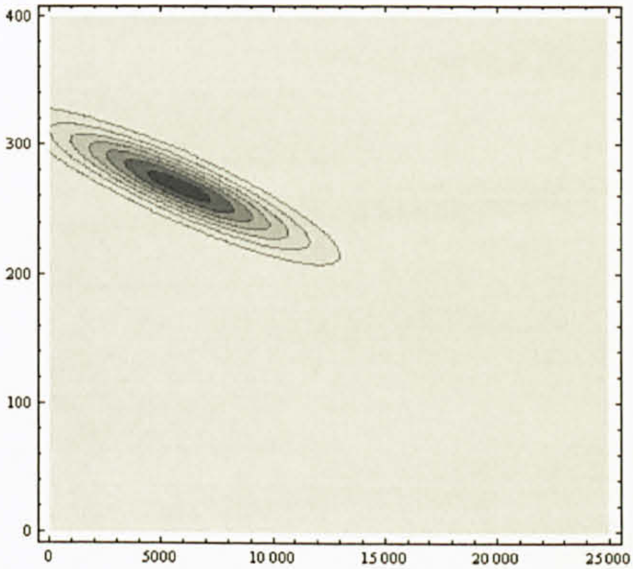


Figure 21: Posterior joint probability density of bored piles at adjacent site

In Figure 21, the y-axis represents the skin friction while the x-axis represents the end bearing capacity. From the figure, it was observed that the highest probability of skin friction is in the range of 220kPa to 245kPa.

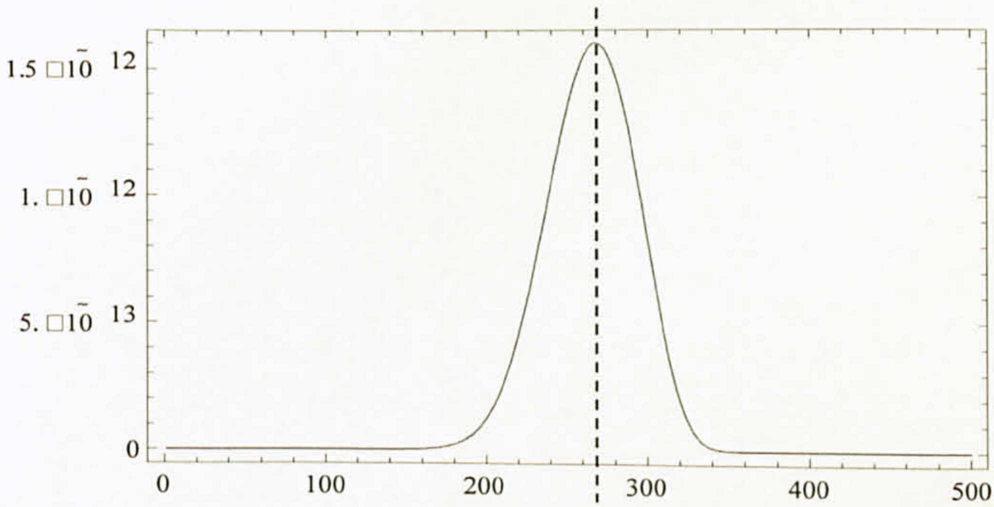


Figure 22: Posterior distribution of unit skin friction of bored piles at adjacent site

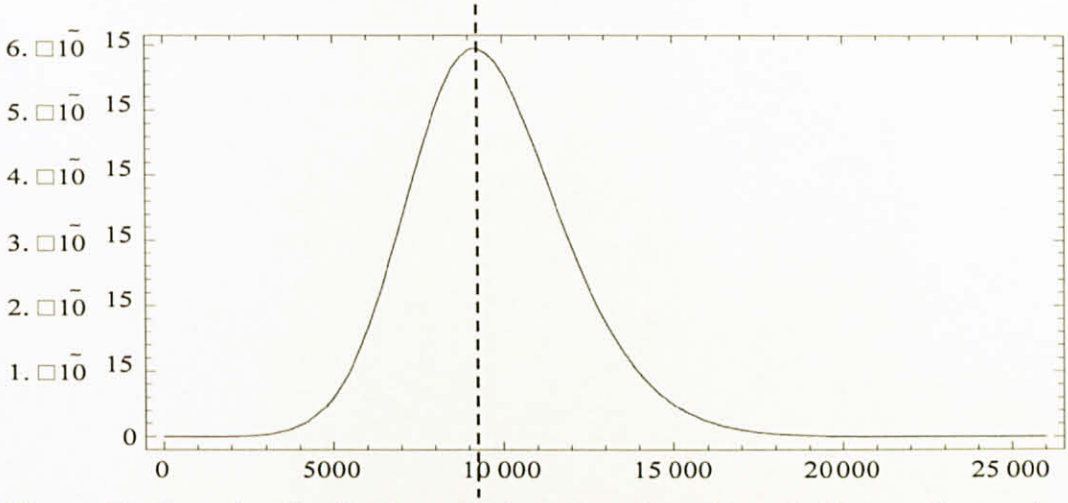


Figure 23: Posterior distribution of unit end bearing of bored piles at adjacent site

As shown in Figure 22, the peak of the graph is 264kPa, therefore the skin friction of bored piles is estimated to be 264kPa. By comparing it to the results obtained at Jalan Pinang site, Jalan Binjai site has higher skin friction than bored piles constructed with or without bentonite at Jalan Pinang site. This is due to the better SPT' N value of the soil at Jalan Binjai site.

Figure 23 shows that the average end bearing value of the bored piles is 9100kN, which is much higher compared to Jalan Pinang site. From the back-calculated results, it can be said that the soil at Jalan Binjai is better than the ones at Jalan Pinang site.

Kuala Lumpur Kenny Hill formation consists of weathered soil of different weathering condition, therefore there would be uncertainties at two different sites. Moreover, both Jalan Pinang site and Jalan Binjai site are almost 1000m apart from each other. Thus, this could explain the difference of about 8% in terms of skin friction of bored piles constructed without bentonite at two different sites.

COMPARISON OF DESIGN PARAMETERS AND BACK-CALCULATED PARAMETERS

Comparison between the design parameters of the test piles obtained from the semi-empirical method and the back-calculated parameters is summarized in the table below:

Table 6: Comparison of Design and Back-calculated Parameters

Pile No.		Skin Friction, Fs (kPa)		End Bearing, Qb (kN)	
		Design	Back-calculated	Design	Back-calculated
With bentonite	PTP1	235.8	227	3141.6	4850
	PTP2	271.2		4523.9	
	BP27	265.5		4523.9	
Without Bentonite	BP85	263.8	253	2356.2	5100
	BP62	242.0		6441.2	
Adjacent Site	PTP2	232	264	2545	9100
	BP120	300		3141.6	

From the table, the average back-calculated skin friction of bored piles with bentonite is lower than the design skin friction with a factor of 1.13. This is due to the effects of bentonite used during construction of bored piles which causing reduction of skin friction of the bored piles. However, for the bored piles constructed without bentonite at Jalan Pinang site as well as bored piles at adjacent site, the back-calculated values of skin friction are quite close to the average value of the design skin friction with a factor of approximately 1.0. As indicated, for bored piles constructed without bentonite, the back-calculation of skin friction tallies with the design skin friction.

While for the case of end bearing of piles, the back-calculated value of bored piles constructed with bentonite is higher than the design values. This is also the same for adjacent site, where the back-calculated end bearing is much higher than it is supposed to be for during design stage. The back-calculation of end bearing value for bored piles constructed without bentonite is slightly higher than the average design value, but it is still within the range of the design values.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

Static pile load tests were conducted on five fully instrumented bored piles, 3 of them with bentonite and the other two without bentonite. Ultimate pile capacity was derived from the load test using Davisson's method. Field parameters such as skin friction and end bearing of the bored piles were back-calculated using probability inverse method based on known pile geometry and ultimate pile capacity. Two different cases were inspected, case 1 is for bored piles constructed with bentonite and case 2 is for the bored piles constructed without bentonite. Comparison of field parameters of different cases gives the effects of bentonite on bored pile especially the skin friction.

It is concluded that the use of bentonite during borehole excavation will affect the properties of soil around pile shafts. The bentonite filter cake formed on the wall of borehole will reduce the skin friction of bored piles to approximately 11%. Bentonite will affect the end bearing resistance of the pile toe as well, but in a smaller percentage, which is approximately 5%.

Generally, most of the bored piles in Malaysia are friction pile, which the bored pile achieves its capacity mainly from the skin friction with little or no contribution from end bearing of pile toe. Therefore, skin friction of pile shaft is given more attention to then the end bearing of pile toe.

RECOMMENDATION

Bentonite is sometimes used to avoid soil collapse during excavation of borehole, however, it also leaves behind negative effects on the pile. Based on the results obtained and discussion on the results, it is recommended that bentonite should be avoided in any construction of bored piles. However, in cases where bentonite is unavoidable, contractors should make sure that appropriate density of bentonite is used. The design of bored piles should also be revised by considering a reduction factor of skin friction, from this research, a factor of 0.15 to 0.2 is suggested. However, to obtain a more accurate reduction factor, more pile load test data should be collected and analyzed.

Although less concern is placed on the end bearing of bored piles, it should be noted that the pile base should be cleaned efficiently, as the presence of soft and compressible materials on the pile base would deteriorate the load-movement behavior at the pile toe.

CHAPTER 6

ECONOMIC BENEFITS

Costing is most of the time, one of the very crucial issues to any construction projects. Since construction projects involving bored piles as the foundation are usually large-scale projects, therefore, design of the bored piles must be done carefully. To make sure that the bored piles are sufficient to take the loads from the structures, a few factors will be considered during design stage. Besides a safety factor of about 2.0 to 2.5, ultimate skin friction factor and ultimate end bearing factor must also be taken into consideration.

From this research, it was found that if bentonite is to be used during boring of boreholes, the skin friction factor should be reduced by 15% to 20%. In this case, longer pile is required to take the applied load. Thus, in terms of economic analysis, this case is not cost beneficial.

Consider BP27 (1200mm diameter, 23m length bored piles) which was constructed with bentonite, a 20% reduction of skin friction factor is equivalent to 20% increased in pile length, this means that the bored pile should be elongated by 4.6m. The estimated additional cost is as shown:

Table 7: Estimated additional cost for construction of BP27

Item	Cost per meter depth of pile	Unit (m)	Sub-total
Boring	RM420	4.6	RM1932.00
Rebar	RM80	4.6	RM368.00
Concrete	RM400	4.6	RM1840.00
		Total	RM4140.00

The calculation above is based on the tender price of a 1200mm bored pile. The required extra length of the bored piles depends on the design pile length, the longer the design pile length, the longer is the additional length required. Besides that, the cost also dependent of the pile diameter, larger pile requires higher cost of boring and higher volume of concrete.

To conduct the analysis of this project, pile load test results are needed. Maintain Load Test on a instrumented test pile costs around RM100,000. In this project, five pile load test results were obtained from five Maintain Load Tests, therefore, the cost of this research is around RM500,000. However, since the pile load test data is obtained from a real construction project, no cost is required for that.

REFERENCES

Balakrishan, E.G., Balasubramanian, A.S. and Phien-wej Noppadol. *Load Deformation Analysis of Bored Piles in Residual Weathered Formation*. Journal of Geotechnical and Geoenvironmental Engineering, Vol.125, Issue 2, pp.122-131. 1999.

Bowles, Joseph E. *Foundation Analysis and Design*. Fifth Edition. McGraw-Hill. 1996.

Chang, M.F. and Brooms, B.B. *Design of Bored Piles in Residual Soils Based On Field-Performance Data*. Canadian Geotechnical Journal, Vol.28, pp.200-209.1991.

Chang, M.F. and Hong, Zhu. *Construction Effect on Load Transfer along Bored Piles.* Journal of Geotechnical and Geoenvironmental Engineering, Vol.130, Issue 130, pp.426-437. 2004.

Chean, S.C., Lee, C.H. *Performance of Bored Piles with Different Construction Methods*. 2006.

Chen, C.S. and Hiew, L.C. *Performance of Bored Piles With Different Construction Methods*. Geotechnical Engineering 159, Issue GE3. 2006.

Coduto, Donald P. *Foundation Design Principles and Practices*. Prentice-Hall. 1994.

Das, Braja M. *Principles of Foundation Engineering*, Fifth Edition. Thomson Brooks / Cole. 2004.

Goh, Anthony T.C *et al. Bayesian Neural Network Analysis of Undrained Side Resistance of Drilled Shaft*. Journal of Geotechnical and Geoenvironmental Engineering. 2005.

Gue, S.S. and Tan, Y.C. *Design and Construction Consideration for Deep Basement*. Lecturer on Design and Construction for Deep Basement. The Institution of Engineers, Malaysia. 1998.

Gue, S.S. *Pile Foundation Design and Construction*. Lecture at KL Infrastructure University College, Kuala Lumpur. 2007.

Gue, S.S., Tan, Y.C. and Liew, S.S. *A Brief Guide to Design of Bored Piles Under Axial Compression – A Malaysia Approach*. Seminar and Exhibition on Bridge Engineering. Association of Consulting Engineers Malaysia. 2003.

Harahap, I.S.H. and Wong, C.W. *Bayesian Inversion of Proof Pile Test: Marcov Chain Monte Carlo Simulation Approach.* 2008.

Kishida, H., Tsubakihara, Y. and Ogura, H. *Pile Loading Tests at Osaka Park Project.* 1992.

Ng, W.L. Sean. *Effects of Construction on the Performance of Larfe Excavated Piles Supported by Bentonite.* Hong Kong University of Science & Technology. 2002.

Soil Investigation Report on Proposed Mixed-Use Development of 5-Star Hotel, Service Apartment & Office Spaces at Lots 70, 71 & 89, Jalan Pinang, Kuala Lumpur. 2005.

Stichman, R.W. *Sealing Boreholes with Sodium Bentonite.* Iowa Groundwater Assoc. Newsletter Vol.2, No.11. 1990.

Tan, Y.C. and Chow, C.M. *Design & Construction of Bored Pile Foundation.* Gue & Partner Sdn Bhd. 2003.

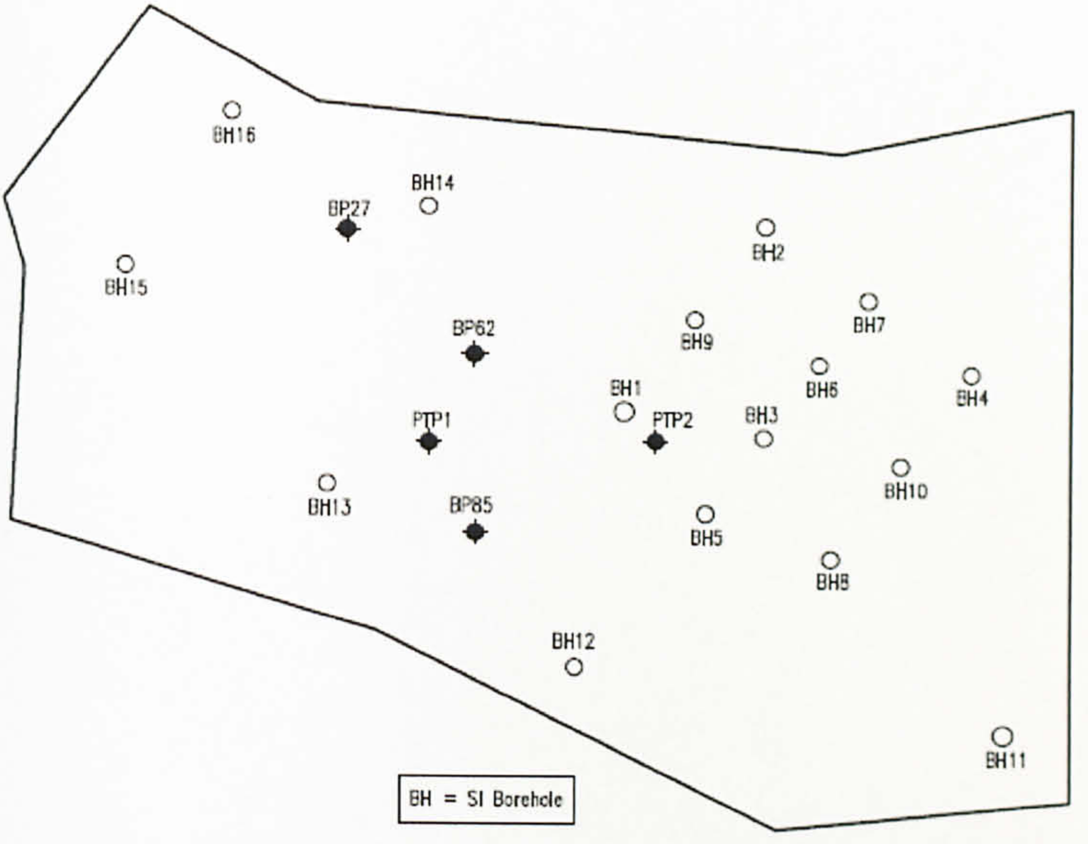
Toh, C.T. *et al. Design Parameters for Bored Piles in a Weathered Sedimentary Formation.* Proceedings of 12th International Conference on Soil Mechanics and Foundation Engineering, Vol.2, pp.1073-1078. 1989.

Tomlinson, Michael and Woodward, John. *Pile Design and Construction Practice*, Fifth Edition. 2008.

Woodward, John. *An Introduction to Geotechnical Processes.* Spon Press, 2005.

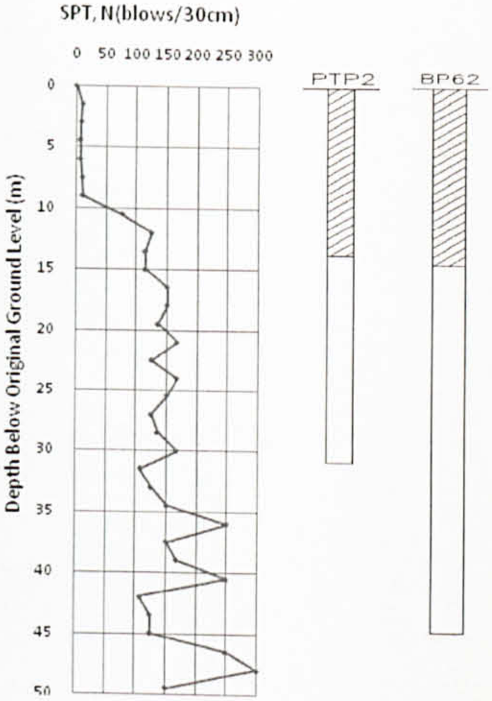
APPENDICES

APPENDIX A: Pile Load Test and Boring Location

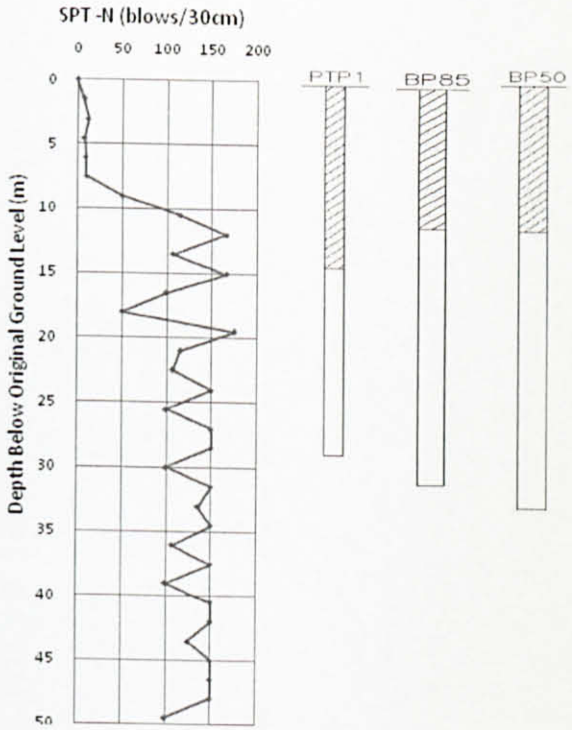


APPENDIX B: SPT'N of Boreholes

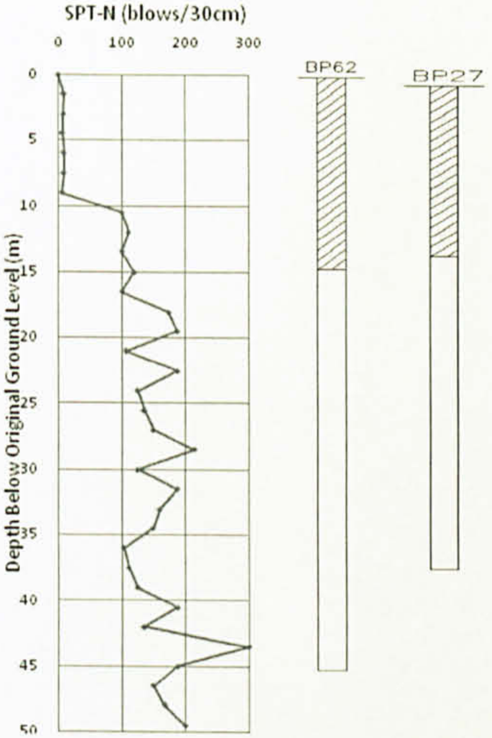
1. BH1 – Adjacent with PTP 2 and BP62



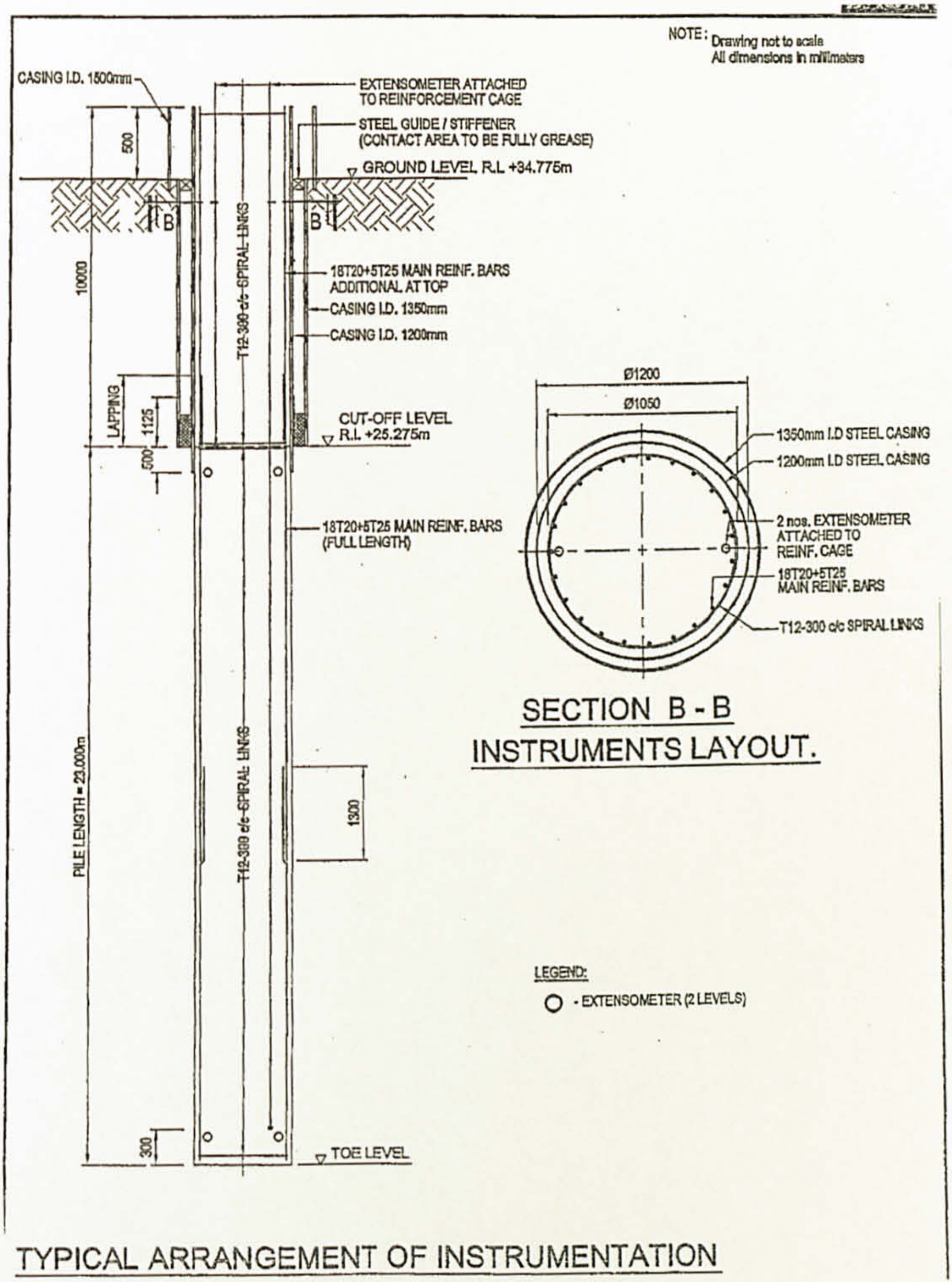
2. BH13 – Adjacent with PTP1 and BP85



3. BH14 – Adjacent with BP62 and BP27



APPENDIX C: Typical Arrangement of Instrumentation of Static Load Test



TYPICAL ARRANGEMENT OF INSTRUMENTATION

APPENDIX D: Design Calculation of Bored Piles at Jalan Pinang Site

1. PTP 1

Pile Diameter : 1000 mm

Cut-off Level (below existing platform level) : 13.82 m

Toe of Pile (below existing platform level) : 28 m

Pile Length : 14.18 m

Max Test Load : 2.5×6800 kN = 17000 kN

SI reference : BH13

k parameter : 2.0

Skin Friction, f_s : $k \times SPT$

Depth From Ground Level (m)	Depth of Soil (m)	Soil SPT (N)	Skin Friction, f_s (kN/m^2)	Shaft Resistance, Q_s (kN)
13.82	1.18	107	214	793.3
15.00	1.50	150	300	1413.7
16.50	1.50	100	200	942.5
18.00	1.50	50	100	471.2
19.50	1.50	150	300	1413.7
21.00	1.50	115	230	1083.8
22.50	1.50	107	214	1008.5
24.00	1.50	150	300	1413.7
25.50	1.50	100	200	942.5
27.00	1.00	150	300	942.5
28.00	-	-	-	-
			Ultimate Shaft Resistance, Q_s	**10425.4**

Bearing Pressure at tip, f_b $= 30 \times$ Pile Tip SPT (N) = 4500 kN/m^2 ($f_b \leq 4000$ kPa)

= 4000 kN/m^2

Ultimate Tip Resistance, Q_b $= f_b \times A_b =$ **3141.6** kN

2. PTP 2

Pile Diameter	: 1200 mm
Cut-off Level (below existing platform level)	: 13.14 m
Toe of Pile (below existing platform level)	: 29.56 m
Pile Length	: 16.42 m
Max Test Load	: 2.5 × 10000 kN = 25000 kN

SI reference : BH1

k parameter : 2.0

Skin Friction, f_s : k × SPT

Depth From Ground Level (m)	Depth of Soil (m)	Soil SPT (N)	Skin Friction, f_s (kN/m^2)	Shaft Resistance, Q_s (kN)
13.14	0.36	125	250	339.3
13.50	1.50	115	230	1300.6
15.00	1.50	115	230	1300.6
16.50	1.50	150	300	1696.5
18.00	1.50	150	300	1696.5
19.50	1.50	136	272	1538.1
21.00	1.50	150	300	1696.5
22.50	1.50	125	250	1413.7
24.00	1.50	150	300	1696.5
25.50	1.50	150	300	1696.5
27.00	1.50	125	250	1413.7
28.50	1.06	136	272	1086.9
29.56	-	-	-	-
			Ultimate Shaft Resistance, Q_s	**16875.3**

Bearing Pressure at tip, f_b = 30 × Pile Tip SPT (N) = 4080 kN/m^2 ($f_b \leq 4000$ kPa)

= **4000 kN/m^2**

Ultimate Tip Resistance, Q_b = $f_b \times A_b$ = **4523.9** kN

3. BP27

Pile Diameter	: 1200 mm
Cut-off Level (below existing platform level)	: 12.567 m
Toe of Pile (below existing platform level)	: 35.567 m
Pile Length	: 23 m
Max Test Load	: 1.5 × 6800 kN = 10200 kN

SI reference	: BH14
k parameter	: 2.0
Skin Friction, f_s	: k × SPT

Depth From Ground Level (m)	**Depth of Soil (m)**	**Soil SPT (N)**	**Skin Friction, f_s (kN/m^2)**	**Shaft Resistance, Q_s (kN)**
12.57	0.93	111	222	780.8
13.50	1.50	100	200	1131.0
15.00	1.50	120	240	1357.2
16.50	1.50	100	200	1131.0
18.00	1.50	173	346	1956.6
19.50	1.50	188	376	2126.2
21.00	1.50	107	214	1210.1
22.50	1.50	188	376	2126.2
24.00	1.50	125	250	1413.7
25.50	1.50	136	272	1538.1
27.00	1.50	150	300	1696.5
28.50	1.50	214	428	2420.3
30.00	1.50	125	250	1413.7
31.50	1.50	188	376	2126.2
33.00	1.50	160	320	1809.6
34.50	1.07	150	300	1206.7
35.57	-	-	-	-
			Ultimate Shaft Resistance, Q_s	**16961.2**

Bearing Pressure at tip, f_b = 30 × Pile Tip SPT (N) = 4500 kN/m^2 ($f_b \leq 4000$ kPa)

= **4000 kN/m^2**

Ultimate Tip Resistance, Q_b = $f_b \times A_b$ = **4523.9** kN

4. BP85

Pile Diameter : 1000 mm

Cut-off Level (below existing platform level) : 10.729 m

Toe of Pile (below existing platform level) : 30.229 m

Pile Length : 19.5 m

Max Test Load : 1.5 × 6800 kN = 10200 kN

SI reference : BH13

k parameter : 2.0

Skin Friction, f_s : k × SPT

Depth From Ground Level (m)	Depth of Soil (m)	Soil SPT (N)	Skin Friction, f_s (kN/m^2)	Shaft Resistance, Q_s (kN)
10.73	1.27	115	230	918.4
12.00	1.50	150	300	1413.7
13.50	1.50	107	214	1008.5
15.00	1.50	150	300	1413.7
16.50	1.50	100	200	942.5
18.00	1.50	50	100	471.2
19.50	1.50	150	300	1413.7
21.00	1.50	115	230	1083.8
22.50	1.50	107	214	1008.5
24.00	1.50	150	300	1413.7
25.50	1.50	100	200	942.5
27.00	1.50	150	300	1413.7
28.50	1.50	150	300	1413.7
30.00	0.23	100	200	143.9
30.23	-	-	-	-
			Ultimate Shaft Resistance, Q_s	**10247.2**

Bearing Pressure at tip, f_b = 30 × Pile Tip SPT (N) = **3000** kN/m^2 ($f_b \leq 4000$ kPa)

Ultimate Tip Resistance, Q_b = $f_b \times A_b$ = **2356.2** kN

5. BP62

Pile Diameter : 1500 mm

Cut-off Level (below existing platform level) : 13.873 m

Toe of Pile (below existing platform level) : 42.873 m

Pile Length : 29 m

Max Test Load : 1.5 × 16000 kN = 24000 kN

SI reference 1 : BH1

k parameter : 2.0

Skin Friction, f_s : k × SPT

Depth From Ground Level (m)	Depth of Soil (m)	Soil SPT (N)	Skin Friction, f_s (kN/m^2)	Shaft Resistance, Q_s (kN)
13.87	1.13	115	230	1224.7
15.00	1.50	115	230	1625.8
16.50	1.50	150	300	2120.6
18.00	1.50	150	300	2120.6
19.50	1.50	136	272	1922.7
21.00	1.50	150	300	2120.6
22.50	1.50	125	250	1767.1
24.00	1.50	150	300	2120.6
25.50	1.50	150	300	2120.6
27.00	1.50	125	250	1767.1
28.50	1.50	136	272	1922.7
30.00	1.50	150	300	2120.6
31.50	1.50	107	214	1512.7
33.00	1.50	125	250	1767.1
34.50	1.50	150	300	2120.6
36.00	1.50	150	300	2120.6
37.50	1.50	150	300	2120.6
39.00	1.50	150	300	2120.6
40.50	1.50	150	300	2120.6
42.00	0.87	107	214	877.4
42.87	-	-	-	-
			Ultimate Shaft Resistance, Q_s	**18803.3**

SI reference 2 : BH14

k parameter : 2.0

Skin Friction, f_s : k × SPT

Depth From Ground Level (m)	Depth of Soil (m)	Soil SPT (N)	Skin Friction, f_s (kN/m^2)	Shaft Resistance, Q_s (kN)
13.87	1.13	100	200	1062.2
15.00	1.50	120	240	1696.5
16.50	1.50	100	200	1413.7
18.00	1.50	150	300	2120.6
19.50	1.50	150	300	2120.6
21.00	1.50	107	214	1512.7
22.50	1.50	150	300	2120.6
24.00	1.50	125	250	1767.1
25.50	1.50	136	272	1922.7
27.00	1.50	150	300	2120.6
28.50	1.50	150	300	2120.6
30.00	1.50	125	250	1767.1
31.50	1.50	150	300	2120.6
33.00	1.50	150	300	2120.6
34.50	1.50	150	300	2120.6
36.00	1.50	103	206	1456.1
37.50	1.50	111	222	1569.2
39.00	1.50	125	250	1767.1
40.50	1.50	150	300	2120.6
42.00	0.87	136	272	1119.0
42.87	-	-	-	-
			Ultimate Shaft Resistance, Qs	**18281.5**

Average Ultimate Shaft Resistance, Q_s =

= **18542.4** kN

Bearing Pressure at tip, f_b = 30 × Pile Tip SPT (N) = **3645** kN/m^2 ($f_b \leq 4000$ kPa)

Ultimate Tip Resistance, Q_b = $f_b \times A_b$ = **6441.2** kN

APPENDIX E: back-calculation of field parameters using mathematica program

Case 1: Bored piles constructed with bentonite

```
clearAll;
L1=0;
D1=1.2;
PLength1=16.42;
DL1=PLength1-L1;
A1=D1*Pi;
P1obs=16500;
s1=1500;

L2=0;
D2=1.0;
PLength2=14.18;
DL2=PLength2-L2;
A2=D2*Pi;
P2obs=3400;
s2=1500;

L3=0;
D3=1.2;
PLength3=23.00;
DL3=PLength3-L3;
A3=D3*Pi;
P3obs=22000;
s3=1500;

rho1[p1_]:=Exp[-(1/2) (p1-P1obs)^2/s1^2]
rho2[p2_]:=Exp[-(1/2) (p2-P2obs)^2/s2^2]
rho2[p3_]:=Exp[-(1/2) (p3-P3obs)^2/s3^2]
rhoD[p1_,p2_,p3_]:=rho1[p1] rho2[p2] rho3[p3]

P1cal[Fs_,Qb_]:=Fs*PLength1*A1+0.25*Qb*D1^2*22/7
P2cal[Fs_,Qb_]:=Fs*PLength2*A2+0.25*Qb*D2^2*22/7
P3cal[Fs_,Qb_]:=Fs*PLength3*A3+0.25*Qb*D3^2*22/7

rhoM1[p1_]:=Exp[-(1/2) (p1-250)^2/30^2]
rhoM2[p2_,p3_]=1;
rhoM[p1_,p2_,p3_]:=rhoM1[p1] rhoM2[p2,p3]
sigmaFQ[Fs_,Qb_]:=rhoM[Fs,Qb] rhoD[P1cal[Fs,Qb],P2cal[Fs,Qb],P3cal[Fs,Qb]]

ContourPlot[-sigmaFQ[Fs,Qb],{Qb,0,20000},{Fs,0,350},PlotRange→All,PlotPoints→50]
```

Case 2: Bored piles constructed without bentonite

```
clearAll;
L1=0;
D1=1.5;
PLength1=29.00;
DL1=PLength1-L1;
A1=D1*Pi;
P1obs=41500;
s1=1500;

L2=0;
D2=1.0;
PLength2=19.500;
DL2=PLength2-L2;
A2=D2*Pi;
P2obs=24200;
s2=1500;

rho1[p1_]:=Exp[-(1/2) (p1-P1obs)^2/s1^2]
rho2[p2_]:=Exp[-(1/2) (p2-P2obs)^2/s2^2]
rhoD[p1_,p2_]:=rho1[p1] rho2[p2]

P1cal[Fs_,Qb_]:=Fs*PLength1*A1+0.25*Qb*D1^2*22/7
P2cal[Fs_,Qb_]:=Fs*PLength2*A2+0.25*Qb*D2^2*22/7

rhoM1[p1_]:=Exp[-(1/2) (p1-250)^2/30^2]
rhoM2[p2_]=4000;
rhoM[p1_,p2_]:=rhoM1[p1] rhoM2[p2]
sigmaFQ[Fs_,Qb_]:=rhoM[Fs,Qb] rhoD[P1cal[Fs,Qb],P2cal[Fs,Qb]]

ContourPlot[-sigmaFQ[Fs,Qb],{Qb,0,20000},{Fs,0,350},PlotRange→All,PlotPoints→50]
```

Case 3: Bored piles from adjacent site

```
clearAll;
L1=0;
D1=0.9;
PLength1=25;
DL1=PLength1-L1;
A1=D1*Pi;
P1obs=10300;
s1=1700;

L2=0;
D2=1.0;
PLength2=25.5;
DL2=PLength2-L2;
A2=D2*Pi;
P2obs=36000;
s2=1700;

rho1[p1_]:=Exp[-(1/2) (p1-P1obs)^2/s1^2]
rho2[p2_]:=Exp[-(1/2) (p2-P2obs)^2/s2^2]
rhoD[p1_,p2_]:=rho1[p1] rho2[p2]

P1cal[Fs_,Qb_]:=Fs*PLength1*A1+0.25*Qb*D1^2*22/7
P2cal[Fs_,Qb_]:=Fs*PLength2*A2+0.25*Qb*D2^2*22/7

rhoM1[p1_]:=Exp[-(1/2) (p1-290)^2/30^2]
rhoM2[p2_]=4000;
rhoM[p1_,p2_]:=rhoM1[p1] rhoM2[p2]
sigmaFQ[Fs_,Qb_]:=rhoM[Fs,Qb] rhoD[P1cal[Fs,Qb],P2cal[Fs,Qb]]

ContourPlot[-sigmaFQ[Fs,Qb],{Qb,0,25000}, {Fs,0,400},PlotRange→All,PlotPoints→50]
```