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Comparison Between Different Diameter and Length of Pile Foundation on Its Bearing Capacity in Soft Soils Using Plaxis 2D Software Modeling

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Abstract: The pile designs with different diameter and length affect its ultimate bearing capacity in marine clay. The marine clay which often found in Malaysia especially at the coastal area are considered as problematic soil type due to its low strength and high compressibility's properties. Many development projects on the marine clay area requires suitable pile foundation design to ensure a strong support to the superstructure. This study will help to determine the best pile design with greatest ultimate bearing capacity by analysing, predicting and comparing the bearing capacity of different pile designs. The Finite Element Analysis (FEA) of Plaxis 2D software was used in this study to help simulate the models of pile and marine clay under load application. Soft Soil Model and Linear Elastic Model were adopted for the simulation of 15 pile models of different length and diameter ranging from 6m to 46m (in length) and 0.3m to 1.0m (in diameter). Chin's method was used to predict the ultimate bearing capacity based on the load-settlement curve. The results show that the bigger the pile diameter, the greater its ultimate bearing capacity. Also, the longer the pile length, the greater its ultimate bearing capacity. As a result, the pile model P (1.0m, D and 46m, L) with ultimate bearing capacity of 2000kN was the best pile design in marine clay. This study became the future reference for engineer to design the best pile design in marine clay and proved the effectiveness of Plaxis D software in virtual pile simulation.

Keywords: Pile, Plaxis 2D, Bearing Capacity, Marine Clay

1. Introduction

Piles are invented especially for the weak soil conditions where shallow foundation is not capable in providing the sufficient strength and support to its superstructure above. This is proven when the

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piles are mostly used in the area where the soil layers are sandier and more clayey. Marine clay consists of high-water content, low density, low frictional force between particles and many other factors that resulting in a very weak, insignificant soil strength. The watery trait of the marine clay causing it easily to change into different shape when load is applied on it. Marine clay is often found in the coastal area of Malaysia where large population is living at the coastal area. The vast construction development at the coastal area requires good design of deep foundation. The engineer will have to decide which types of the pile foundation is most suitable and can achieve the greatest bearing capacity in the soil especially in the soft clay. This is required to prevent the large settlement and collapse of the superstructure built on it. The research is aiming at determining the pile design with greatest bearing capacity when driven into the marine clay. In order to achieve that, three objectives have to be fulfilled, which are to analyse in terms of bearing capacity for different diameter and length of pile on marine clay by using Plaxis 2D software, to predict the bearing capacity of pile based on the relationship of applied load and settlement, and to analyse relationships of the effects of pile diameter and length to bearing capacity.

The Plaxis 2D software was used to conduct the simulation of piles in marine clay and Finite Element Analysis. The parameters of marine clay used in this study are taken from costal area of Bagan Datoh District, Perak, Malaysia which is stated in the [1]. The soft soil model is applied with inputting of several parameters such as modified compression index (λ), modified swelling index (κ), friction angle (φ), effective cohesion (c), and dilatancy angle (Ψ), saturated unit weight (γ_{sat}) and others. This allowed the Plaxis 2D software to create a marine clay soil's condition for the pile foundation simulation [7]. Linear Elastic Model is used to simulate the circular pile ranging from 0.3m to 1m (diameter) and 6m to 46m (Length). The study did not consider the effects of number of joints of the precast pile foundation to the bearing capacity. It was considered as single continuous pile inserted into soil layers without joints due to long pile design. The concrete pile parameters such as unsaturated unit weight, modulus of elasticity and poisson's ratio will be entered as input [2].

2. Literature Review

The review of past studies or journals made strong references and did contribute to this research in many ways. The main parameters used for simulation and the method to calculate the bearing capacity were based on the past studies.

2.1 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a computerised numerical analysis program that designed for interpreting the complex problems in scientific and engineering fields. FEA is used to perform the numerical analysis of foundation settlement and bearing capacity [12]. The modelling of the soil layers and pile design can be analysed through FEA by using Plaxis 2D.

2.2 Soft Soil Model and Linear Elastic Model

Based on the several past studies, the input parameters for the soil and pile material are taken and listed in the tables below. The data shown will provide an example of the input parameters required to perform the Soft Soil Model and Linear Elastic Model in the numerical analysis by using Plaxis 2D. Some of the parameters are not provided by the past studies because the differences in conducting the simulation which based on their own conditions and scenarios. Tables 1 and 2 presenting the examples of pile material and soil input parameters from the past studies.

Table 1: The Example of Pile's Material Input Parameters (Linear Elastic)

No	Input Parameters	References		
		[9]	[8]	[14]
1.	Type of Material	-	Non porous concrete	-
2.	Unit Weight (kN/m^3)	24	24	24
3.	Modulus of Elasticity, E (kN/m^2)	2.6x10^7	2.57x10^7	35000
4.	Poisson's Ratio,	0.15	0.2	0.3

Table 2: The Example of Soil Input Parameters (Soft Soil Model)

No	Input Parameters	References			
		[1]	[4]	[14]	[6]
1.	Modified Compression index (λ)	0.186	0.13	0.103	0.093
2.	Modified Swelling Index (κ)	0.070	0.05	0.015	0.041
3.	Effective Cohesion, c (kN/m^2)	10	13.4	-	3
4.	Angle of Dilation, Ψ (°)	-	-	-	-
5.	Friction angle, φ (°)	-	0	33	22

2.3 Chin's Method

Chin's method is used to calculate the pile's bearing capacity. The load-settlement relation is found to be hyperbolic by using Chin's method on the tests conducted in field and laboratory (with piles). In this method, prediction of the ultimate bearing capacity is calculated by plotting a graph between the settlement per load against the settlement [3]. The graph is also named as graph of shear deformation against the shear deformation per shear force. Then, a linear trend can be taken from the graph. A linear equation can be formed from the relationship of the graph. Based on the linear equation, the inverse of the slope (1/m) will become the ultimate load which is equivalent to the ultimate bearing capacity of pile. The equation below shows the relationship of settlement per load against settlement (load-settlement relationship) in Chin's method [5]:

$$\Delta/P = m\Delta + C \tag{1}$$

$$P = \frac{1}{\mathrm{m}} \tag{2}$$

P = Load (kN); Δ = Settlement (m); m = slope of the straight line; C = y-intercept of the straight line
Figure 1 shows the example for graph of settlement/load (m/kN) against settlement (m) in Chin's method [8].

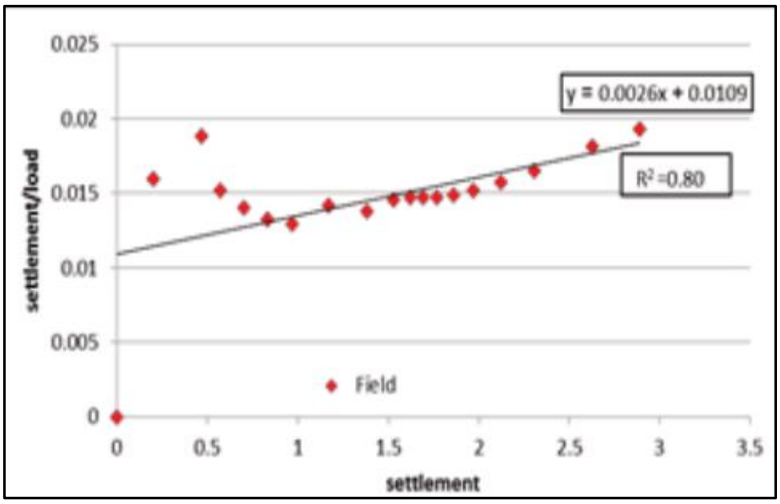

Figure 1: The Graph of Settlement/load against Settlement in Chin's method

3. Methodology

Methodology is the combination of theoretical and systematic analysis of method that is used in the field of study or research. It is a technique that helps resolving the research problems with numerous procedure [11]. In this study, the pile and marine clay parameters were used to conduct the simulation. The marine clay parameters were taken from the coastal area in Bagan Datoh District, Perak, Malaysia. The soil layer of the marine clay was fixed at 60m, with 5 layers in total and only consists of pure marine clay without other soil types. A summary of marine clay input parameters is listed in the Table 3 below.

Table 3: Summary of Marine Clay Input Parameters

No	Input Parameters	[1]				
1.	Soil Layer	Crust	Upper Soft Clay 1	Lower Soft Clay 2	Lower Clay 1	Lower Clay 2
2.	Soil Depth (m)	0 - 2	2 - 6	6 - 12	12 - 18	18 - 60
3.	Soil Type			All Marine Clay		
4.	Water Level			Same level as the soil surface		
5.	Modified compression index, λ	0.189	0.186	0.139	0.120	0.113
6.	Modified swelling index, κ	0.069	0.070	0.054	0.049	0.053
7.	Unit Weight, γ_{sat} (kN/m3)	13.6	14	14.3	13.8	14
8.	K_x (m/day)	$2.01\text{x}10^{-4}$	$6.23\text{x}10^{-4}$	$3.45\text{x}10^{-4}$	$4.0\text{x}10^{-4}$	$2.12\text{x}10^{-4}$
9.	K_y (m/day)	$1.01\text{x}10^{-4}$	$3.12\text{x}10^{-4}$	$1.67\text{x}10^{-4}$	$2.0\text{x}10^{-4}$	$1.06\text{x}10^{-4}$
10.	Poisson's ratio, ν			0.15		
11.	NC_{K0}			0.965		
12.	Cohesion, c (kN/m^2)	6	10	15	22	30
13.	Dilatancy angle, Ψ (°)			-		
14.	Friction angle, φ (°)			-		

A total of 15 pile models were used and concrete pile's parameters were based on the [9]. A total of 15 piles with different diameter and length labelled from "A" to "P" are shown in Table 4 below. The Table 5 shows the summary for input parameters of the piles which will be used for the simulation later.

Table 4: Pile Models and its Specification used in this Study

No	Pile Model	Diameter (m)	Length (m)
1	A	0.3	6
2	B	0.3	12
3	C	0.4	6
4	D	0.4	12
5	E	0.5	6
6	F	0.5	18
7	G	0.6	12
8	H	0.6	18
9	I	0.6	36
10	J	0.8	18
11	K	0.8	36
12	L	0.8	46
13	M	1.0	18
14	N	1.0	36
15	P	1.0	46

Table 5: Summary of Piles Input Parameters

No	Input Parameters	
1.	Type of Material	Precast Concrete
2.	Material Model	Linear Elastic
3.	Drainage Type	Non porous
4.	Unit weight, γ_{sat} (kN/m^3)	24
5.	Modulus of Elasticity, E (kN/m^2)	$2.6\text{x}10^7$
6.	Poisson's Ratio, ν	0.15

The modelling of circular piles was done using the *"Axisymmetry"* mode and linear elastic model while soft soil model was used for marine clay simulation. For settlement and load relationship (load-settlement), the node was selected for the X-Axis whereas the stress point was selected for the Y-Axis. The $|u|$ of *Total Displacement* under *Deformations* is chosen for X-axis. The σ_1 of *Principal Total Stress* under *Stresses* was chosen for Y-axis. A curve of Settlement against load, σ_1 was generated.

4.0 Results and Discussions

Based on the load-settlement relationship, the graph of settlement/load against settlement were plotted and the piles' bearing capacity were calculated. This section shows the results and discussions of this research to fulfill the objectives.

4.1 Calculation of Pile's Ultimate Bearing Capacity

The Table 6 shows the summary of calculated bearing capacity from pile model A to model P using the gradient of settlement/load relationship.

Table 6: Summary of Calculated Ultimate Bearing Capacity for all Pile Models

No	Pile Model	Diameter (m)	Length (m)	Calculated Ultimate Bearing capacity (kN)
1	A	0.3	6	7.65
2	B	0.3	12	23.33
3	C	0.4	6	18.94
4	D	0.4	12	25.00
5	E	0.5	6	31.75
6	F	0.5	18	136.36
7	G	0.6	12	116.67
8	H	0.6	18	102.04
9	I	0.6	36	657.89
10	J	0.8	18	144.33
11	K	0.8	36	833.33
12	L	0.8	46	1304.35
13	M	1	18	212.12
14	N	1	36	1025.64
15	P	1	46	2000.00

4.2 Validation of Numerical Analysis

The application of numerical analysis such as Finite Element Analysis (FEA) has become very popular recently. However, case studies were reviewed to ensure the accuracy of the numerical analysis in getting the accurate outcome. A total of 3 past studies about the calculation of ultimate bearing capacity of single pile in soil were reviewed. According to [9], the percentage difference of the predicted ultimate bearing capacity between the analytical and Finite Element Analysis method was 39%. The soil type consists of clay and sand. Meanwhile, [10] indicated that there was 36% difference in both methods used to calculate the bearing capacity given the pile diameter of 0.9m, 34m length and several sandy soil layers. The pile models B, G, H, I, J, K and N were within the ±10% of the range of 39%. Study from [13] show that there was around 13% of difference when compared with both FEA and analytical method in calculating the ultimate bearing capacity. Pile model C, E and M did fall in the range of ±10% of the difference. Nevertheless, there was many influencing factors and difference in those studies, including the soil types, pile diameter and length, soil properties, loading on pile and others. These factors and difference resulted in the variation of the percentage difference of analytical and Finite Element Analysis method in calculating ultimate bearing capacity. However, the validation of the Finite Element Analysis for this study was in comply with the general range of the bearing capacity from the reviewed past studies. Table 7 shows the summary of Percentage Difference in Ultimate Bearing Capacity (U.B.C) from Past Studies.

Table 7: Summary of Percentage Difference in Ultimate Bearing Capacity from Past Studies

No	Parameter	Validation between past studies and present results					
		[12]	Present Results	[10]	Present Results	[13]	Present Results
1.	Pile Specification	0.35m(D) 17m (L)	0.6m(D) 18m (L) ***Pile Model H***	0.9m (D) 34m (L)	0.8m/1.0m (D) 36m/36m (L) ***Pile Model K/N***	- (m) 4m (L)	0.4m(D) 6m (L) ***Pile Model C***
2.	Soil Type	Silty Clay (3m) Sand (4m) Sand (3m)	Marine Clay (60m)	Silty Fine Sand (13m) Dense to Very Dense Sand (0.7m) Calacrenite (27.3m) Sandstone (5m)	Marine Clay (60m)	Hard Rock (4m)	Marine Clay (60m)
3.	Analytical Method, (U.B.C) kN	919	161.06	9015	586.43/ 7330.04	3000	21.78
4.	FEA Method, (U.B.C), kN	558	102.04	12252	833.33/ 1025.64	3400	18.94
5.	Percentage Difference, %	39	36.86	36	42.1/39.92	13	13.05
6.	Range	$\pm 3\%$		$\pm 6\%/\pm 4\%$		$\pm 0.05\%$	

4.4 Effect of Pile Diameter and Length to its Ultimate Bearing Capacity

The relationship of pile diameter and length to its bearing capacity is shown in this subsection. The comparison was made among pile with same diameter but different length and vice versa. Bar chart was used to display the comparison between the diameter and length for each condition. According to Figure 2, the increase of 6m to 12m with 0.3 pile diameter, the ultimate bearing capacity was increased by around 3x the original bearing capacity (7.65kN to 23.33kN). based on the general trend of the graphs, there was around 1.5x or 2.5x increases in ultimate pile bearing capacity for every 6m increases in pile length for every other pile diameter. On the other hand, the ultimate bearing capacity of pile increases at the rate of 1.1x to 1.3x of its original value with every increase of 0.1m in pile diameter. For example, for pile length of 36m, the pile with diameter of 0.7m (760kN) is 1.15x of 0.6m (657kN) in terms of ultimate bearing capacity. All the pile models followed the similar increasing trend when pile diameter is increased.

However, Figure 3 and Figure 6 also proven that for pile length of 18m, or pile located around the Lower Clay 1, the ultimate bearing capacity of pile was slightly lower than the smaller pile diameter (12m) with same pile length. Moreover, the increase of pile diameter for the same 18m pile length also did not have significant impact on the ultimate bearing capacity until the pile diameter is doubled. This might be caused by the weak cohesion strength of that particular soil layer. The situation may lead to the weight of pile becoming a burden instead of providing essential bearing capacity. Figure 2 to 7 shows the Graph of Ultimate Bearing Capacity against Pile Diameter / Pile length for selected pile models respectively.

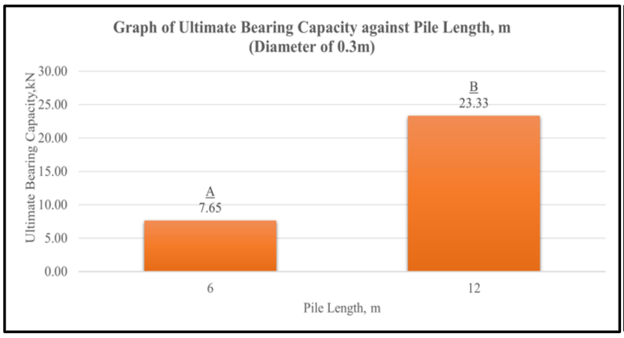

Figure 2: 0.3m (D) & 6m and 12m (L)

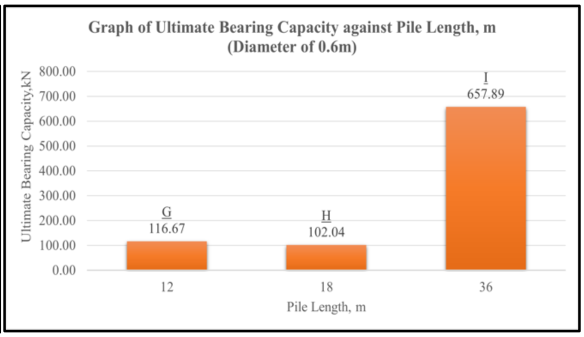

Figure 3: 0.6m (D) & 12m, 18m and 36m (L)

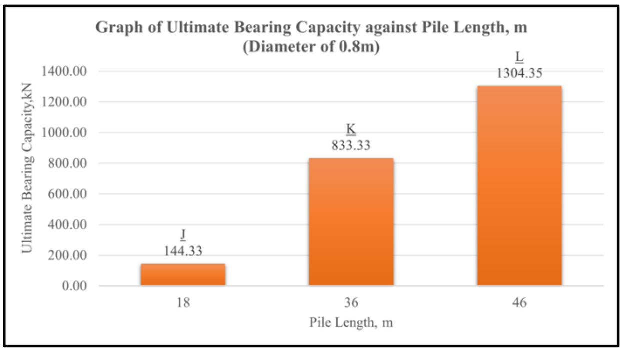

Figure 4: 0.8m (D) & 18m, 36m and 46m (L)

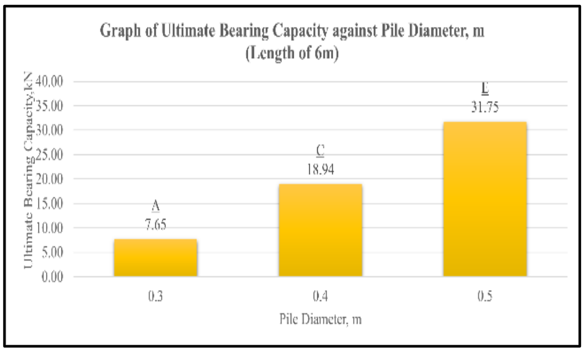

Figure 5: 6m (L) & 0.3m, 0.4m and 0.5m (D)

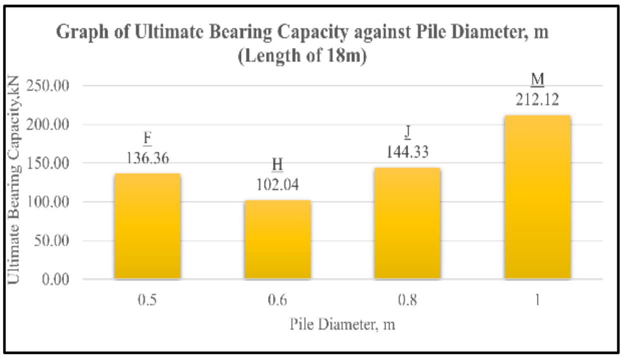

Figure 6: 18m (L) & 0.5m, 0.6m, 0.8m and 1.0m (D)

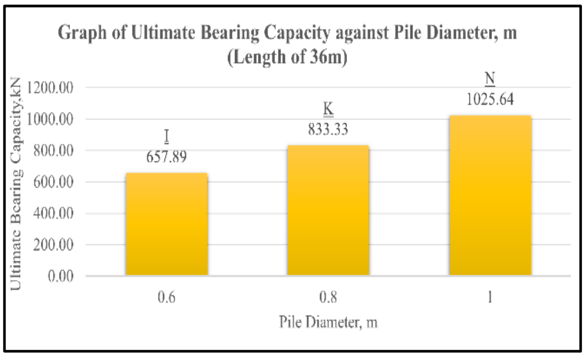

Figure 7: 36m (L) & 0.6m, 0.8m and 1.0m

According to Figure 8 and Figure 9, both graphs showing that the greater the pile diameter and length, the steeper the gradient, thus the greater the increases in ultimate bearing capacity. The analysis of the effect of pile length and diameter to its ultimate bearing capacity proven that the increases in pile length and pile diameter will increase its ultimate bearing capacity. Figure 8 and Figure 9 shows the graph of ultimate bearing capacity against pile diameter and of against the pile length for all pile models respectively.

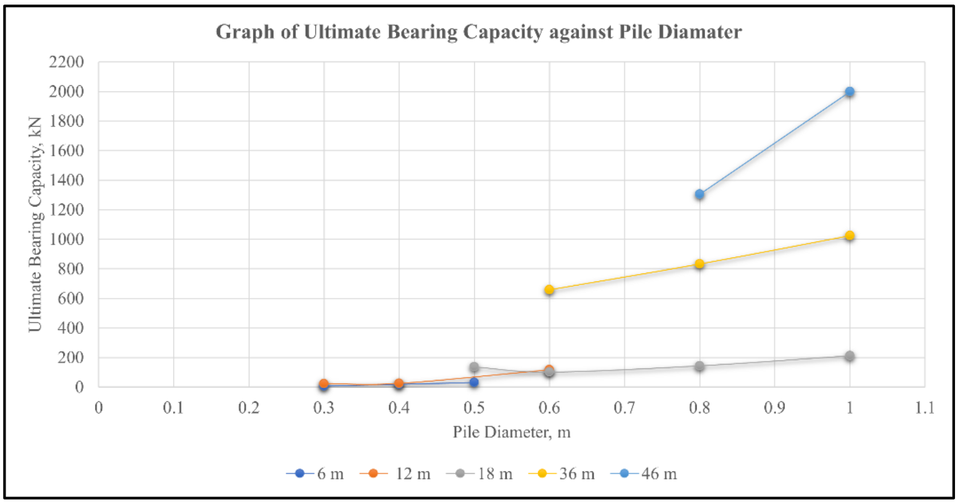

Figure 8: Graph of Ultimate Bearing Capacity against Pile Diameter

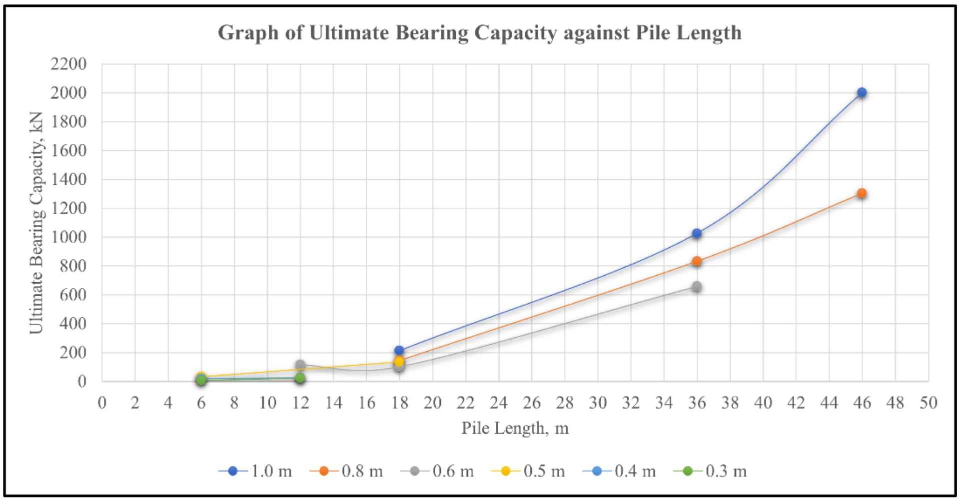

Figure 9: Graph of Ultimate Bearing Capacity against Pile Length

4.5 Others Influencing Factors to Bearing Capacity

There were others influencing factors that affects the bearing capacity of piles in marine clay. For instances, all parameters of soil used in modelling including compression index, friction angle, swelling index, water level and cohesion. However, cohesion, c (kN/m^2) will be explained in this section as important influence to pile's bearing capacity others than the pile length and diameter. The cohesion of the marine clay used in this study was increased from outer layer to the deepest layer. From the crust to lower layer 2, a total of 5 layers of marine clay, the cohesion increased from 6, 10, 15, 22 to 30kN/m^2. This has resulted in the strength of the soil increased indirectly when cohesion was increased. The cohesion contributed to the increases of soil strength and thus, resulted in the increased of bearing capacity of pile when it was piled deeper into the marine clay. Thus, when the pile was longer, it reached deeper soil layer with higher cohesion. The bearing capacity of the pile was increased. Therefore, the cohesion of the soil layer also influenced the bearing capacity of the pile when the pile was longer. However, if the pile was bigger in diameter but no longer in length, then the cohesion of the soil layer has lesser effect to the bearing capacity as the upper layers of marine clay was lower in cohesion than the deeper soil layers. This explained the Models I, K, L, N and P have much greater bearing capacity when compared to the models with same pile diameter.

4. Conclusion

According to the results, with the increase of pile length, the ultimate bearing capacity was increased given the same diameter of pile was set. Also, the results also proven that with the constant pile length, the increase of pile diameter also increase the ultimate bearing capacity. Hence, two correlations were made.

1. The bigger the pile diameter, the greater its ultimate bearing capacity
2. The longer the pile length, the greater its ultimate bearing capacity

With the above correlations, the pile model P (1.0m in diameter and 46m in length) with the greatest ultimate bearing capacity of 2000kN was chosen as the best pile model when embedded in the marine clay. The simulations of 15 pile models with different length and diameter were completed using Plaxis 2D software. Chin's method proven to be useful in predicting the ultimate bearing capacity of piles. Hence, all three objectives were achieved.

There were recommendations for further research on this study. First, application of Plaxis 3D software to simulate the piles with different shapes and dimensions to get more accurate results. Second, the study of behavior of pile in soft soil can be expanded to other type of soft soil such as alluvium soil, colluvium soil and peat soil for more diverse results.

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