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DETERMINING THE CAPACITY OF A PILE WITH THE CONDITION OF ENCOUNTERING SOIL WITH MANY LENSES

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ABSTRACT

In a structural construction, one of the important parts that need to be made to support the structure is the foundation. The foundation plays a crucial role, so if there is a settlement in the foundation of a structure, an investigation is needed to address it. In a project in Serpong, South Tangerang, there is a case where there is a layer of soil with lenses, which is a condition where there is a hard soil layer with an N-SPT value greater than 50 and a thickness of about 1-4 m, this hard soil layer is located between two layers of soil with an N-SPT values less than 50. The presence of these soil lenses, located at depths of 8 m, 14 m, 24 m, and 42 m with varying thicknesses, cannot be identified through the Cone Penetration Test (CPT) and is feared to cause a settlement in the pile foundation. This is because the maximum capacity of the cone penetration test is only up to 2.5 tonf and cannot penetrate these soil lenses. This research uses soil data in the form of two boring log data, which will then be analyzed and compared for the axial bearing capacity and the settlement that occurs if the foundation piles occupy each soil condition that has a soil lens layer. The Meyerhoff and Hanna method is used to calculate the ultimate bearing capacity, while the Alpha Thomlinson method is used to calculate the settlement.

Keywords: *foundation, bearing capacity, lens, settlement*

1. PREFACE

Introduction

The lens layer is formed due to the flow of sedimentation transport and then becomes a relatively thin and hard layer. This layer is often considered as the actual hard soil layer, but there is a soft layer underneath with an N-SPT value of < 50. This layer can break due to being too thin during the construction process, and in addition to layer breakage, because this lens layer is located above the soft soil layer, significant foundation settlement can occur in a short period, affecting the safety and lifespan of the structure. The thickness of this lens layer is also directly proportional to the increase in the diameter of the pile, which in turn affects the increase in bearing capacity. Therefore, it can be concluded that the thickness of the lens layer is directly proportional to foundation pile's increase in the bearing capacity.

Problem Formulation

Due to the possibility of cracks in the lens layer or settlement caused by the soft layer underneath it. It is necessary to analyze the amount of foundation piles' bearing capacity and settlement, accompanied with consideration of the dominant type of settlement that occurs in this lens layer.

Meyerhoff's and Hanna's Method

Bearing capacity is defined as the ability of soil to withstand external loads and pressure on the soil safely without causing shear failure and significant settlement. The ultimate bearing capacity (q_{ult}) can be formulated as stated below:

$$q_{ult} = q_p + q_s - W_p$$

q_p is the end bearing (kN), q_s is the skin friction (kN), and W_p is the weight of pile (kN).

The ultimate bearing capacity of a firm clay soil layer overlying soft clay soil can be formulated as follows:

$$q_u = 5.14\ Su2 \left(1+\frac{0.2B}{L}\right)+\left(1+\frac{B}{L}\right)\left(\frac{2C\alpha H}{B}\right)+\gamma sat\ Df < qt$$

Which,

$$q_t = 5.14\ Su1 \left(1+\frac{0.2B}{L}\right)+\gamma sat\ Df$$

In the other hand, for a single-layered clay soil under undrained conditions, where $\phi = 0$, the bearing capacity for ultimate condition can be formulated as:

$$Q_P \approx N_C^* S_{u2} A_p = 9 S_{u2} A_p$$

A_p is the cross-sectional area (m^2), γ_{sat} is the soil unit weight (kN/m^3), D_f is the pile length (m), C_α is the cohesion bearing capacity (kPa), H is the thickness of the layer (m), N_c^* is the bearing capacity factor. S_{u1} is the cohesion for undrained soil layer above the soil layer at the pile tip (kPa), S_{u2} is the cohesion for undrained soil layer below the soil layer at the pile tip (kPa), B is the length of the pile (m), and L is the width of the pile (m).

The α method in calculating Q_s

Based on the total stress analysis, the α method, the mantle resistance in the clay layer can be formulated as follows:

$$f = \alpha . S_u$$

This method is usually used to calculate short-term load capacity on fine-grained soil. Sladen (1992) showed that:

$$\alpha = C\left(\frac{\bar{\sigma}_o'}{S_u}\right)^{0.45}$$

The value of α varies and can also be determined through Table 1. The value of α obtained from the formula may differ from that given in Table 1 because the formula for finding the value of α is a value for the vertical effective stress and cohesion for undrained condition.

Table 1. Variation of α Value
[1]

$\frac{S_u}{P_a}$	α
≤ 0,1	1,00
0,2	0,92
0,3	0,82
0,4	0,74
0,6	0,62
0,8	0,54
1,0	0,48
1,2	0,42
1,4	0,4
1,6	0,38
1,8	0,36
2,0	0,35
2,4	0,34
2,8	0,34

Here is the formula for calculating Q_s:

$$Q_s = \sum f\, p\, \Delta L = \sum \alpha\, S_u\, p\, \Delta L$$

To determine bearing capacity that are allowable (q_u), the Allowable Stress Design (ASD) method is usually used, where the bearing capacity for ultimate condition (q_{ult}) is divided by the safety factor (F).

$$q_u = \frac{q_{ult}}{F}$$

Where, q_u and q_{ult} are in kN, and q is the external load, so:

$$q \leq q_u$$

Based on SNI 8460:2017, the safety factor for shallow foundations is a minimum of 3 and for deep foundations is a minimum of 2.5.

Settlement

Settlement is a condition where the ground surface subsides and can be caused by various factors, such as design, soil layer conditions, foundation dimensions, large structural loads, and changes in soil volume. There are three components of soil settlement that result in total soil settlement

(S_t), namely Primary Consolidation Settlement (S_c), Secondary Consolidation Settlement (S_S), and Elastic Settlement (S_E), so the equation is formulated as follow:

$$S_t = S_e + S_c + S_s$$

Elastic settlement or immediate settlement usually occurs within 0-7 days and with constant in moisture content. The total elastic settlement or immediate settlement that occurs in a single pile consists of three components, namely the elastic shortening of the pile ($S_{e(1)}$), the settlement of the pile end due to applied load ($S_{e(2)}$), and the settlement due to the friction between the surrounding soil and the pile resulting from the applied load ($S_{e(3)}$) [1] Thus, it can be formulated as follows:

$$S_e = S_{e(1)} + S_{e(2)} + S_{e(3)}$$

Where,

$$S_{e(1)} = \frac{(Q_{wp} + \xi Q_{ws})L_p}{A_p E_p}$$

$$S_{e(2)} = \frac{q_{wp} D}{E_s} \cdot (1-\mu_s^2) I_{wp} = \frac{Q_{wp} C_p}{D q_p}$$

$$S_{e(3)} = \left(\frac{Q_{ws}}{pL_p}\right)\frac{D}{E_s} \cdot (1-\mu_s^2) I_{ws} = \frac{Q_{ws} C_s}{L_p q_p}$$

While settlement in a single pile can be formulated as described above, settlement in a pile group ($S_{g(e)}$) can be formulated as follows:

$$S_{g(e)} = \sqrt{\frac{B_g}{D}}\, S_e$$

Table 2. C_p Value

Table Source: Vesic (1977)

Soil Type	Driven Pile	Drilled Pile
Sand (*dense to loose*)	0,02-0,04	0,09-0,18
Clay (*stiff to soft*)	0,02-0,03	0,03-0,06
Silt (*dense to loose*)	0,03-0,05	0,09-0,12

Primary consolidation settlement occurs over a longer period and is greater than immediate settlement. Primary consolidation settlement occurs when a certain saturated soil layer is exposed to a constant load, and the water drains out, causing a change in volume in the soil layer. The following is the formula for primary consolidation settlement based on its stress condition:

Normally consolidated, ($\sigma_c' \leq \sigma_o'$)

$$\Delta S_c = \left[\frac{C_c H}{1+e_o}\right] \log\left[\frac{\sigma_o' + \Delta\sigma_i'}{\sigma_o'}\right]$$

Overconsolidated (OC_1), $(\sigma'_o+\Delta\sigma'_q \leq \sigma'_c)$

$$\Delta S_c = \frac{C_s H}{1+e_o} \log\left(\frac{\sigma'_o+\Delta\sigma'_i}{\sigma'_c}\right)$$

Overconsolidated (OC_2), $(\sigma'_o+\Delta\sigma'_q > \sigma'_c)$

$$\Delta S_c = \frac{C_s H}{1+e_o} . \log\frac{\sigma'_c}{\sigma'_o} + \frac{C_c H}{1+e_o} . \log\left(\frac{\sigma'_o+\Delta\sigma'_i}{\sigma'_c}\right)$$

$$S_c = \Sigma\Delta S_c$$

C_c is the compression index, ΔS_c is the pile group's primary consolidation settlement (m), e_0 is the initial void ratio of the soil, C_s is the recompression index, σ'_o is the effective overburden pressure (kN/m^2), σ'_c is the preconsolidation pressure (kN/m^2), S_c is the total primary consolidation settlement of the pile group (m), and H is the thickness of the soil layer (m).

Meanwhile, secondary consolidation happens or occurs as soon as the primary consolidation is complete, where pore water pressure becomes zero and there is plastic adjustment of soil particles. Secondary consolidation can be formulated as follows:

$$S_s = C_\alpha . \frac{H}{1+e_p} . \log\left(\frac{t_2}{t_1}\right)$$

$$e_p = e_0 - \Delta e_{primary}$$

$$\Delta e = C_c \log\left(\frac{\sigma'_o+\Delta\sigma'}{\sigma'_o}\right)$$

e_0 is soil's initial void ratio, e_p is the final void ratio after primary consolidation, Δe is the change in void ratio, H is layer thickness (m), t_2 is the time required for secondary consolidation (s), t_1 is the time required for primary consolidation (s), C_α is the secondary compression index (s), and S_s is the total secondary consolidation settlement of the group pile (m).

2. RESEARCH METHOD

The research methodology used to complete this study was carried out sequentially as follows:

Literature Review

Conducting a literature review with the aim of understanding the theories and characteristics of layer lens soil and searching for formulas used to analyze of foundation piles' bearing capacity and settlement.

Data Collection and Processing

The soil investigation data used in this study were obtained from a project site in Serpong, South Tangerang. The data were organized informatively in the form of N-SPT values in two Boring logs, as well as the determination of soil properties, types, and parameters for ease of understanding.

Analysis and Discussion

The analysis of bearing capacity and settlement was conducted by examining the foundation piles that penetrate each layer of soil with a lens in two boring log data, which were then compared to several results. The method used in calculating the end bearing capacity was the Meyerhof and

Hanna method, while the skin friction capacity was calculated using the Alpha Thomlinson method.

3. RESULT AND DISCUSSION

Soil Parameters

Using soil data consisting of two boring log data, empirical formula correlation was performed to obtain the required soil parameters as shown in Table 3 and Table 4.

Table 3. Soil Data Boring 1

ELEVATION (m)		DEPTH (m)	TYPE OF SOIL	CONSISTENCY	N-SPT	γ_{sat} (kN/m³)	e_0	E_u (MPa)	S_u (kPa)	Cc	Cs	P'_c (kPa)
0	2	1	*CLAY*	*SOFT*	4	16.5	2.8	5	14	1.02	0.41	82
2	4	3	*SILT*	*SOFT*	5	17	2.8	6	17	0.74	0.39	82
4	6	5	*SILT*	*SOFT*	4	17	2.8	5	14	0.74	0.39	59
6	8	7	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	1278
8	10	9	*SILT*	*HARD*	35	20	0.4	38	115	0.10	0.06	776
10	12	11	*SILT*	*MEDIUM STIFF*	6	17.75	0.8	7	20	0.22	0.11	83
12	14	13	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	1125
14	16	15	*SILT*	*VERY STIFF*	17	19.25	0.5	19	56	0.13	0.07	284
16	18	17	*SILT*	*STIFF*	10	18.5	0.6	11	33	0.16	0.09	143
18	20	19	*CLAY*	*HARD*	31	21	0.4	33	102	0.13	0.06	568
20	22	21	*CLAY*	*VERY STIFF*	20	19.5	0.5	22	66	0.23	0.08	321
22	24	23	*CLAY*	*VERY STIFF*	18	19.5	0.5	20	59	0.23	0.08	276
24	26	25	*CLAY*	*HARD*	50	21	0.4	54	164	0.13	0.06	966
26	28	27	*CLAY*	*VERY STIFF*	22	19.5	0.5	24	72	0.23	0.08	340
28	30	29	*CLAY*	*VERY STIFF*	16	19.5	0.5	17	53	0.23	0.08	225
30	32	31	*CLAY*	*HARD*	33	21	0.4	36	108	0.13	0.06	545
32	34	33	*CLAY*	*VERY STIFF*	26	19.5	0.5	28	86	0.23	0.08	399
34	36	35	*CLAY*	*VERY STIFF*	30	19.5	0.5	32	99	0.23	0.08	471
36	38	37	*CLAY*	*VERY STIFF*	25	19.5	0.5	27	82	0.23	0.08	370
38	40	39	*CLAY*	*VERY STIFF*	30	19.5	0.5	32	99	0.23	0.08	459
40	42	41	*SAND*	*VERY DENSE*	50	21	0.4	54	164	0.23	0.05	857
42	44	43	*CLAY*	*HARD*	32	21	0.4	34	105	0.13	0.06	484
44	46	45	*CLAY*	*VERY STIFF*	26	19.5	0.5	28	86	0.23	0.08	370
46	48	47	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	828
48	50	49	*CLAY*	*VERY STIFF*	26	19.5	0.5	28	86	0.23	0.08	362
50	52	51	*CLAY*	*HARD*	31	21	0.4	33	102	0.13	0.06	446
52	54	53	*CLAY*	*VERY STIFF*	30	19.5	0.5	32	99	0.23	0.08	425
54	56	55	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	796
56	58	57	*CLAY*	*HARD*	31	21	0.4	33	102	0.13	0.06	434
58	60	59	*CLAY*	*VERY STIFF*	29	19.5	0.5	31	95	0.23	0.08	396

Table 4. Soil Data Boring 2

ELEVATION (m)		DEPTH (m)	TYPE OF SOIL	CONSISTENCY	N-SPT	γ_{sat} (kN/m³)	e_0	E_u (MPa)	S_u (kPa)	Cc	Cs	P'_c (kPa)
0	2	1	*CLAY*	*MEDIUM STIFF*	5	17.5	0.8	6	17	0.44	0.13	107
2	4	3	*CLAY*	*MEDIUM STIFF*	6	17.5	0.8	7	20	0.44	0.13	102
4	6	5	*SILT*	*VERY STIFF*	16	19.25	0.5	17	53	0.13	0.07	322
6	8	7	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	1255
8	10	9	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	1193
10	12	11	*SILT*	*VERY STIFF*	27	19.25	0.5	29	89	0.13	0.07	532
12	14	13	*SILT*	*HARD*	50	20	0.4	54	164	0.10	0.06	1107
14	16	15	*SILT*	*VERY STIFF*	16	19.25	0.5	17	53	0.13	0.07	259
16	18	17	*SILT*	*VERY STIFF*	14	19.25	0.5	15	46	0.13	0.07	214
18	20	19	*SILT*	*VERY STIFF*	27	19.25	0.5	29	89	0.13	0.07	474
20	22	21	*SILT*	*VERY STIFF*	25	19.25	0.5	27	82	0.13	0.07	421
22	24	23	*SILT*	*HARD*	39	20	0.4	42	128	0.10	0.06	718
24	26	25	*CLAY*	*VERY STIFF*	16	19.5	0.5	17	53	0.23	0.08	232
26	28	27	*CLAY*	*STIFF*	15	18.5	0.6	16	50	0.32	0.09	210
28	30	29	*CLAY*	*VERY STIFF*	23	19.5	0.5	25	76	0.23	0.08	353
30	32	31	*CLAY*	*HARD*	38	21	0.4	41	125	0.13	0.06	649
32	34	33	*CLAY*	*VERY STIFF*	28	19.5	0.5	30	92	0.23	0.08	437
34	36	35	*CLAY*	*VERY STIFF*	27	19.5	0.5	29	89	0.23	0.08	412
36	38	37	*CLAY*	*VERY STIFF*	29	19.5	0.5	31	95	0.23	0.08	444
38	40	39	*CLAY*	*VERY STIFF*	20	19.5	0.5	22	66	0.23	0.08	276

Lapisan lensa

Pile Bearing Capacity

After obtaining the correlated soil data, calculations are carried out to determine the bearing capacity on axial ax Lens Soil Layers . The calculation uses the Punching Shear method from

Meyerhoff and Hanna as well as the Alpha Thomlinson method for pile shaft's bearing capacity. The cross-sectional dimension of the pile is round with a diameter of 0.6 m. Thus, the calculation results were obtained as shown in Table 5 and Table 6.

Table 5. Summary of Bearing Capacity of Pile on Lens Layer Boring 1

Depth (m)	Q_p (Ton)	Q_s (Ton)	W_p (Ton)	$Q_{allowable}$ (Ton)
8	33.12	39.92	5.43	23.79
14	36.52	103.51	9.5	46.5
26	44.04	247.47	17.64	98.96
42	55.54	512.75	28.5	198.01

Table 6. Summary of Bearing Capacity of Pile on Lens Layer Boring 2

Depth (m)	Q_p (Ton)	Q_s (Ton)	W_p (Ton)	$Q_{allowable}$ (Ton)
8	33.12	48.42	5.43	27.19
14	36.52	130.99	9.5	57.5
24	35.89	252.22	16.29	98.96

Settlement

The three main component that make up the total settlement that occurs are immediate settlement, primary, and secondary consolidation, which shown in Table 7 – Table 13.

Table 7. Boring 1 (Depth 8 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(5.33-6m)	5.6667	0.0408	0.0588	0.0645
(6-18 m)	12	-	0.0371	0.0684
(18-30 m)	24	-	0.0036	0.0099
(30-42 m)	36	-	0.0011	0.0029
(42-52 m)	47	-	0.0008	0.0008
(52-60 m)	56	-	0.0005	0.0005
TOTAL		0.0408	0.1021	0.1471

Table 8. Boring 1 (Depth 14 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(17.33-18 m)	17.6667	0.0187	0.0032	0.0032
(18-30 m)	24	-	0.0074	0.0200
(30-42 m)	36	-	0.0017	0.0045
(42-52 m)	47	-	0.0005	0.0012
(52-60 m)	56	-	0.0007	0.0007
TOTAL		0.0187	0.0135	0.0296

Table 9. Boring 1 (Depth 26 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(9.33-18 m)	13.6667	0.0261	0.0236	0.0415
(18-30 m)	24	-	0.0045	0.0122
(30-42 m)	36	-	0.0013	0.0033
(42-52 m)	47	-	0.0009	0.0009
(52-60 m)	56	-	0.0006	0.0006
TOTAL		0.0261	0.0309	0.0585

Table 10. Boring 1 (Depth 42 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(28-30 m)	29	0.0155	0.0045	0.0045
(30-42 m)	36	-	0.0028	0.0072
(42-52 m)	47	-	0.0007	0.0016
(52-60 m)	56	-	0.0009	0.0009
TOTAL		0.0155	0.0090	0.0142

Table 11. Boring 2 (Depth 8 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(5.33-6m)	5.6667	0.0373	0.0136	0.0263
(6-10 m)	8	-	0.0284	0.0527
(10-14 m)	12	-	0.0106	0.0167
(14-24 m)	19	-	0.0062	0.0107
(42-52 m)	28	-	0.0019	0.0048
(52-60 m)	36	-	0.0034	0.0035
TOTAL		0.0373	0.0642	0.1146

Table 12. Boring 2 (Depth 14 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(9.33-10 m)	9.6667	0.0228	0.0052	0.0088
(10-14 m)	12	-	0.0161	0.0255
(14-24 m)	19	-	0.0080	0.0137
(42-52 m)	28	-	0.0022	0.0056
(52-60 m)	36	-	0.0039	0.0039
TOTAL		0.0228	0.0354	0.0575

Table 13. Boring 2 (Depth 24 m)

Layer thickness	z (m)	Se (m)	Sc (m)	Ss (m)
(16-24 m)	20	0.0198	0.0089	0.0153
(42-52 m)	28	-	0.0030	0.0076
(52-60 m)	36	-	0.0049	0.0049
TOTAL		0.0198	0.0168	0.0277

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusion

- Based on the analysis and bearing capacity calculation, the obtained bearing capacity is 198.0162 tons at a depth of 42 m.
- Based on the calculation results, the total settlement of the pile at each depth that does not meet the allowable settlement requirement, which is 1 inch.
- The clay soil below the lens layer has an N-SPT of 15, which is a soft soil that causes the settlement to be even greater.
- Based on the settlement calculation, the largest settlement occurs at 8 m depth with an elastic settlement of 0.0408 m, primary consolidation settlement of 0.1021 m, secondary consolidation settlement of 0.1471 m, with a total settlement of 0.289912 m or 28.9912 cm.
- The secondary consolidation settlement is the largest type of settlement that occurs, which is 0.1471 m, while the primary consolidation settlement is 0.1021 m and the elastic settlement is 0.0408 m.

Recommendation

- The lens layer is not recommended to be used as an end-bearing for foundation piles due to the high risk of excessive settlement that exceeds the allowable limit.
- The lens layer can be used as an end-bearing if the loads from the structure above are not significant or if the lens layer can support the load.
- Additional foundation piles are needed because the pile's load-bearing capacity is smaller than the planned load and the settlement is greater than the allowable limit.
- If the the load from the structure above is large, it is advisable to penetrate the lens layer until it meets the actual hard soil layer for end-bearing of the foundation pile.
- There are four factors that affect the choice of foundation, namely building type or function, site location in earthquake-prone areas, lens layer thickness, and lens layer strength.

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