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Evaluation of Empirical Formulas to Estimate Axial Capacity of Bored Pile in West Java, Indonesia

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ABSTRACT Pile foundation is part of the substructure that plays an important role in carrying and supporting the load acting on it. Therefore, a proper foundation design by estimating the bearing capacity of pile foundation is needed to ensure the safety of the building foundation. To achieve better estimation of pile capacity, analysis of the axial bearing capacity should be verified by pile test results such as Static Loading Test or dynamic test with a Pile Driving Analyzer. Based on the pile test data, the values of the skin friction and end bearing resistance can be back calculated, and hence it can be used in the calculation of pile bearing capacity using empirical methods. In this study, bearing capacity analysis was performed for drilled pile foundations, which had been tested using Static Loading Test and Pile Driving Analyzer. The analysis was carried out by comparing the results of empirical calculations for each test pile with the results of field tests. The calculation results were then compared to the empirical adhesion factor (alpha) method, which is commonly used by practicing engineers in Indonesia, according to the methods proposed by Kulhawy (1984), Reese & Wright (1977), and Reese & O'Neil (1988). Based on the 104 test piles data, the results are more in good agreement with the adhesion factor proposed by Kulhawy (1984) with a correlation of undrained shear strength, cu of 8 N_{SPT}, a correlation of unit skin friction for sandy soils of 2.2 N_{SPT}, and a correlation of unit end bearing for sandy soils of 70 $N_{SPT\text{-}ave.}$

KEYWORDS Foundation; Axial Bearing Capacity; Bored Pile

1 INTRODUCTION

The determination of the axial load and settlements that a foundation undergoes plays a vital role in its planning phase of a foundation. In order to ascertain the actual axial bearing capacity, load tests should be employed on test piles. However, the load test results are generally time-consuming and not suitable for designing phase. Therefore, empirical methods are commonly utilized for predicting end-bearing capacity and skin friction of pile foundations. By doing so, it allows for faster analysis and design processes.

Numerous assumptions and correlations have been formulated and analytically proven by many experts to determine soil parameters and correlations used in the analysis of axial bearing capacity of foundations (Meyerhof (1976), Kulhawy (1984), Reese & Wright (1977), Reese & O'Neil (1988)). However, it is worth highlighting that the empirical correlations available in existing literature have not adequately incorporate the test results specifically from Indonesia. Most of empirical relationships used in Indonesia have not been well-documented and exist primarily as reports specific to certain locations.

This study was conducted to validate the efficacy of commonly employed empirical methods in Indonesia and to contribute to adding a database in form of a literature about pile bearing capacity tests of drilled pile foundations. The results of this study are expected to provide recommendations to practicing engineers regarding the utilization of empirical methods for estimating the axial bearing capacity of bored piles.

2 AXIAL BEARING CAPACITY METHOD

The general calculation of the ultimate bearing capacity of a single-pile foundation can be done using the following formula:

$$Q_u = Q_p + Q_s \qquad (1)$$

Where $Q_p = A_p q_p$, $Q_s = \sum p.\Delta L.f_s$, Q_u = ultimate bearing capacity of the pile (tons), Q_p = end bearing capacity of the pile (tons), Q_s = skin friction capacity of the pile (tons), A_p = cross-sectional area of the pile (m^2), q_p = end bearing resistance per unit area (tons/m^2), p = perimeter of the pile cross-section (m), ΔL = total length of the pile (m), f_s = skin friction resistance per unit area (tons/m^2).

In predicting the axial bearing capacity for pile foundations, correlations based on commonly utilized theories are employed. For calculating the end-bearing capacity in cohesive soil, the general equation $q_p = N_c \times c_u$ is used, where $N_c = 9$ and c_u = the cohesion of the soil below the pile tip under undrained conditions (kN/m^2). Then, the end bearing capacity for sandy soil is calculated using the procedure outlined by Reese & Wright (1977), which is q_p = 70NSPT-ave (kN/m^2), where $N_{SPT-ave} = \frac{N_1+N_2}{2}$; N_1 = average N value from the base of the pile to 10D above; N_2 = average N value from the base of the pile to 4D below.

In addition, the calculation for skin friction resistance for sandy soil is determined by using commonly used correlations with NSPT data, which is the average value of the Meyerhof (1976) and Reese & Wright (1977) calculation methods, with $f_s = 2 \times N_{SPT}\ (kN/m^2)$. For clayey soil, $f_s = \alpha \times c_u$ is used, where α (alpha) is the adhesion factor.

Adhesion Factor (α) is the correlation between shear resistance and undrained shear strength of the soil (Coduto, 2001). This factor can be determined by analyzing the results of pile load tests, which then formulated into a correlation equation. Ideally, it is recommended to use a correlation that is site-specific, customized for a particular field location, and used to design other piles with various diameters and lengths at that specific location. However, due to the lack of site-specific data, it is common to utilize previously formulated values of α. This study will be discussing the commonly used adhesion factor, which are Kulhawy (1984), Reese and Wright (1977), and Reese and O'Neil (1988) method.

Based on Reese and Wright (1977) method, the adhesion factor for bored piles is 0.55. Furthermore, according to Kulhawy (1984), the value of the adhesion factor, α, depends on the undrained shear strength, Su, with alpha tending to decrease with the increase of Su values, as shown in Figure 1. Additionally, Reese and O'Neil (1988) formulated a table of adhesion factor values for various ranges of undrained shear strength, as shown in Table 1

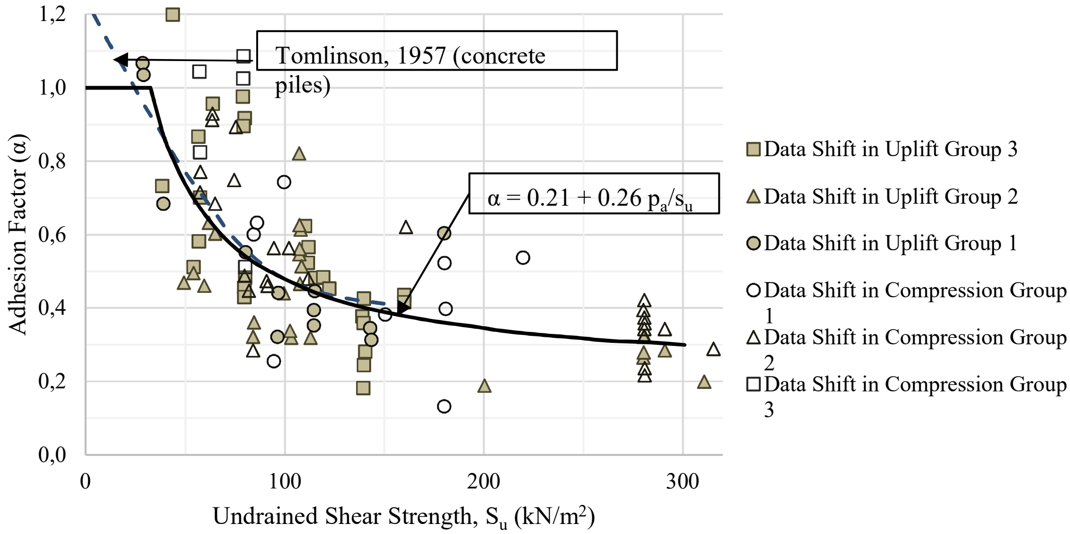


Figure 1. Correlation between the adhesion factor and undrained shear strength (s_u) (Kulhawy, 1984)

Table 1. Correlation between adhesion factor and s_u (Reese & O'Neil, 1988)

Undrained Shear Strength (s_u) kPa			Value of α
	<	200	0.55
200	-	300	0.49
300	-	400	0.42
400	-	500	0.38
500	-	600	0.35
600	-	700	0.33
700	-	800	0.32
800	-	900	0.31
	>	900	Rock

3 METHODOLOGY

The data used in this study consisted of soil investigation data and pile tests of bored pile foundations. The soil investigation included Standard Penetration Test (SPT) data from 104 boreholes. The soil investigation data was obtained from the West Java Toll Road construction project. From the data, it was known that the bored piles had a diameter of 120 cm or 1.2 m. Soil profile was compiled from the Standard Penetration Test results and then summarized based on the soil type. Figure 2 shown a snippet of the soil profile that was compiled.

The field-testing data of bored pile foundations included axial bearing capacity obtained through Static Loading Test (SLT) and Pile Driving Analyzer (PDA) from the Toll Road Project in West Java. The axial bearing capacity was also calculated with empirical equations and the results were compared with the pile tests data. The comparison was back calculated to determine the proposed coefficient factor in the empirical equations.

This research process was started with the calculation for the axial bearing capacity based on the interpretation of SPT data and processing the pile tests data from SLT and PDA results. Then, the coefficient factors for c_u, f_s, and q_p were determined through a series of iterative steps. Iterations were carried out by categorizing cases based on the soil type layers. The coefficient for c_u was determined by using soil data that only involves all-clay soil layers. Then, the c_u coefficient gained from the first step would be utilized in determining the coefficient for the skin-friction resistance for sands (f_s). To determine the correlation of fs for sand, the soil data that was used was soil layers consisting of sands or clays with the pile tip on the clay layer. Finally, by integrating the coefficient of c_u and fs for sand from previous iterations, the coefficient factor for end bearing resistance for sand (q_p) was established using soil data with the pile tip on the sand layer. The calculation of bearing capacity was carried out for each adhesion factor based on (1) Kulhawy (1984), (2) Reese & Wright (1977), and (3) Reese O'Neil (1988).

Data Tanah	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9	P-10	P-11	P-12	P-13	P-14	P-15	P-16	P-17	P-18	P-19	P-20	P-21	P-22	P-23	P-24	P-25
0.00 - -1.00																									
-1.00 - -2.00																									
-2.00 - -3.00	5	4	9	6	4	7	4	2	3	10	10	9	7	10	6	7	2	10	3	2	2	3	5	5	2
-3.00 - -4.00																									
-4.00 - -5.00	6	3	13	5	3	7	3	6	4	4	4	5	32	6	3	32	4	13	4	9	9	4	7	7	9
-5.00 - -6.00																									
-6.00 - -7.00	3	4	11	3	6	3	6	6	1	5	5	3	8	10	4	8	4	15	5	5	5	5	9	9	9
-7.00 - -8.00																									
-8.00 - -9.00	9	3	12	5	4	1	4	5	5	2	2	4	9	4	5	9	6	9	3	10	10	8	12	12	10
-9.00 - -10.00																									
-10.00 - -11.00	>50	4	13	8	8	2	8	7	5	3	3	6	11	7	6	11	2	17	5	>50	>50	14	19	19	11
-11.00 - -12.00																									
-12.00 - -13.00	21	9	9	11	10	5	10	8	7	10	10	4	7	8	8	7	12	16	20	>50	>50	51	37	37	4
-13.00 - -14.00																									
-14.00 - -15.00	22	23	12	13	7	5	7	7	7	11	11	7	15	5	17	15	47	25	38	>50	>50	23	41	41	8
-15.00 - -16.00																									
-16.00 - -17.00	31	>50	48	18	8	6	8	20	5	9	9	12	7	17	34	7	52	26	23	>50	>50	53	47	47	24
-17.00 - -18.00																									
-18.00 - -19.00	16	50	>50	55	15	37	15	19	14	20	20	18	50	22	>50	50	>50	42	33	>50	>50	51	45	45	31
-19.00 - -20.00																									
-20.00 - -21.00	22	52	35	>50	24	21	24	>50	13	26	26	43	>50	>50	>50	>50	>50	42	>50	>50	>50	>50	50	50	18
-21.00 - -22.00																									
-22.00 - -23.00	23	>50	>50	>50	18	43	18	>50	55	45	45	>50	>50	>50	>50	>50	54	>50	>50	32	32	29	>50	>50	21
-23.00 - -24.00																									
-24.00 - -25.00	41	>50	>50	>50	>50	55	>50	>50	32	40	40	42	>50	>50	>50	>50	39	29	>50	34	34	30	>50	>50	37
-25.00 - -26.00																									
-26.00 - -27.00	>50	51	>50	>50	>50	56	>50	>50	32	>50	>50	>50	>50	>50	>50	>50	43	33	>50	>50	>50	33	>50	>50	50
-27.00 - -28.00																									
-28.00 - -29.00	>50	>50	>50	57	>50	>50	>50	>50	55	>50	>50	>50	>50	>50	>50	>50	32	46	>50	>50	>50	40	50	50	>50
-29.00 - -30.00																									
-30.00 - -31.00	>50	50	>50	55	>50	>50	>50	>50	>50	>50	>50	46	50	60	>50	50	>50	>50	50	29	29	21	42	42	35
-31.00 - -32.00																									
-32.00 - -33.00	31	39	34	26	33	10	33	>50	>50	35	35	51	>50	40	33	>50	51	>50	>50	>50	>50	55	>50	>50	43
-33.00 - -34.00																									
-34.00 - -35.00	26	9	45	45	>50	12	>50	12	>50	60	60	27	>50	21	39	>50	>50	>50	>50	50	50	52	>50	>50	24
-35.00 - -36.00																									
-36.00 - -37.00	>50	>50	>50	>50	>50	33	>50	11	61	60	60	38	>50	19	34	>50	>50	>50	>50	>50	>50	54	>50	>50	27
-37.00 - -38.00																									
-38.00 - -39.00	22	>50	>50	>50	56	28	56	>50	>50	50	50	47	>50	25	>50	>50	47	>50	>50	57	57	51	>50	>50	30
-39.00 - -40.00																									

Clay	
Color Index	N_{SPT}
Very Soft	0-4
Soft	4-6
Medium	6-15
Stiff	16-25
Hard	>25

Sand	
Color Index	N_{SPT}
Loose	0-10
Medium	11-30
Dense	31-50
Very Dense	>50

Figure 2. Segment of deep boring summary from the West Jawa toll road project

In each iteration, the coefficient factor for c_u, f_s for sand, and q_p for sand values were determined by evaluating the results based on statistical criteria. These included the coefficient of determination (R2), which measures how well the calculated results align with actual field measurements, and also the ratio of the calculated results over the pile tests results (k). Additionally, other indicators such as mean value and standard deviation were utilized to assess the consistency and difference between the two sets of data. After acquiring the coefficients for the correlations in each stage, these values were utilized until a bearing capacity calculation equation was established. Each adhesion factor method would also be compared to identify the adhesion factor methods that produce the most reliable results based on the available data.

4 RESULTS AND DISCUSSION

The testing data used in this study includes Static Loading Test (SLT) and Pile Driving Analyzer (PDA). The data obtained from the static loading test of a pile was provided in the form of load-settlement curves of the test pile. Each curve of the bored pile was interpreted using methods such as Davisson, Mazurkiewicz, and Chin. From the three interpretations, the minimum values were used to represent the ultimate bearing capacity of the pile. The data from the Pile Driving Analyzer was presented in the form of Summary Results obtained from CAPWAP and the case method. This data provides information about the pile description, the forces experienced by the pile, and the displacement that occurs.

The axial bearing capacity of the bored pile foundation was calculated based on soil parameter data obtained from field tests, specifically the Standard Penetration Test (SPT). The data from the bored piles was then used to calculate the axial bearing capacity of the bored pile foundation using previously described empirical methods. These empirical methods utilize calculation coefficients formulated by previous researchers, and coefficients that result in a better correlation with the obtained soil data will be determined. The calculations were performed for each adhesive factor method, namely Kulhawy's method (1984) (I), Reese & Wright's method (1977) (II), and Reese & O'Neil's method (1988) (III). Subsequently, the results of each calculation were tabulated and compared to the PDA and SLT test results. As an example of comparison, the comparison of several foundation piles to the SLT and PDA data is shown respectively in Table 3 and Table 3.

Table 2. Example of comparison of bored pile bearing capacity data for adhesion factor models against SLT data

Pile Number	Length of Pile	Q_{ult} (ton)				Ratio of Empirical Calculation/SLT		
		SLT	Empirical Calculation					
	m		I	II	III	I	II	III
P 05	32.53	1252	859.85	932.49	890.97	0.68	0.74	0.71
P 070	37	1583.34	987.60	1155.72	1105.04	0.62	0.73	0.69
P 155	29.4	1856	1080.08	1410.76	1247.88	0.58	0.76	0.67
P 195	39	1500.34	1243.93	1522.78	1471.31	0.82	1.01	0.98
P 206	32.75	1670.5	1074.78	1476.88	1319.07	0.64	0.88	0.79

I = Kulhawy Method (1984)
II = Reese & Wright (1977)
III = Reese & O'Neil (1988)

Table 3. Example of comparison of bored pile bearing capacity data for adhesion factor models against PDA data

	Pile Number	Length of Pile	PDA	Empirical Calculation			Ratio of Empirical Calculation/PDA		
		m		I	II	III	I	II	III
Q_{ult} (ton)	P 014	34.4	1380.16	906.66	1006.82	965.77	0.66	0.73	0.70
	P 060	22.5	819.44	662.91	631.41	631.41	0.81	0.77	0.77
	P 122	30.2	1225.84	1253.15	1284.54	1284.54	1.02	1.05	1.05
	P 219	37.9	1161.76	1251.64	1378.28	1359.91	1.08	1.19	1.17
	P 287	34.5	1244.24	923.072	1106.27	1046.32	0.74	0.89	0.84
Q_s (ton)	P 014	34.4	1259.44	775.93	876.08	835.04	0.62	0.70	0.66
	P 060	22.5	756.160	412.062	380.57	380.57	0.54	0.50	0.50
	P 122	30.2	1148.960	849.640	881.03	881.03	0.74	0.77	0.77
	P 219	37.9	1120.960	1052.427	1179.06	1160.69	0.94	1.05	1.04
	P 287	34.5	1151.920	773.659	956.85	896.91	0.67	0.83	0.78
Q_p (ton)	P 014	34.4	120.72	130.74	130.74	130.74	1.08	1.08	1.08
	P 060	22.5	63.280	250.85	250.85	250.85	3.96	3.96	3.96
	P 122	30.2	76.880	403.51	403.51	403.51	5.25	5.25	5.25
	P 219	37.9	40.800	199.22	199.22	199.22	4.88	4.88	4.88
	P 287	34.5	92.320	149.41	149.41	149.41	1.62	1.62	1.62

I = Kulhawy Method (1984)
II = Reese & Wright (1977)
III = Reese & O'Neil (1988)

The illustration shown in Figure 3 is one of the test piles, specifically pile number P70, in the comparison of the three methods to obtain the alpha value.

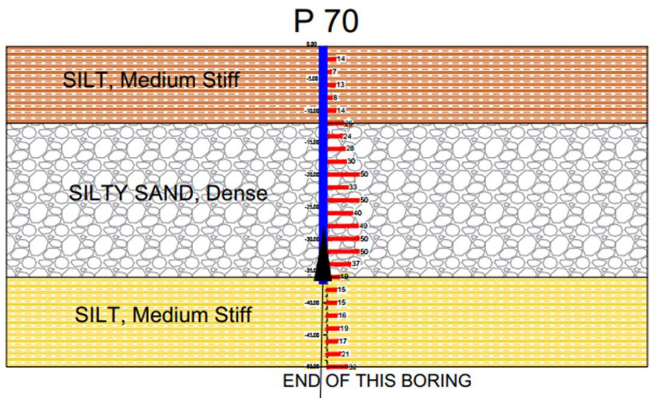


Figure 3. Illustration of soil profile on Pile P70

The comparison results were evaluated based on their relationship using statistical criteria. In this study, statistical criteria such as the coefficient of determination, mean value, and standard deviation were used. To obtain the R-squared values for each calculation method, a "best-fit" line equation will be determined. The "best-fit" line was formed by plotting points that were considered to best represent those points. In this case, the points refer to the plot between the independent variable (axial bearing capacity calculation of the bored pile (SI)) and the dependent variables (PDA and SLT). The straight line formed represents the result of linear regression analysis. From the "best-fit" line, ratio between calculation method over the pile tests results would also be obtained in the form of y=kx equation, with k as the ratio between the two data. As an example, the obtained R2 and k values were tabulated in Table 4.

Table 4. Comparison of R^2 and k values (empirical)

Q_{ult}			
Test	Model	R^2	k
PDA	I	0.9702	0.8712
	II	0.9635	1.0035
	III	0.9701	0.9558
SLT	I	0.9393	0.9149
	II	0.9333	1.083
	III	0.9379	1.0204
Q_s			
Test	Model	R^2	k
PDA	I	0.9672	0.7009
	II	0.9426	0.8470
	III	0.9561	0.6370
Q_p			
Test	Model	R^2	k
PDA	all	0.7615	2.1705

I = Kulhawy Method (1984)
II = Reese & Wright (1977)
III = Reese & O'Neil (1988)

The coefficient of determination values was assessed based on the strength of the relationship between two variables according to Sarwono (2006). It is known that all coefficients of determination values are above 0.75, indicating a very strong correlation. Therefore, each model can be considered suitable for use with the obtained test data. However, the uniformity of the calculation data obtained at the testing location might also play a part in these results.

Other statistical criteria, such as mean values and standard deviations, were also calculated for comparison. These criteria were based on the ratio of bearing capacity calculations for each method and field testing. The comparison for Q_{ult} calculation is shown in Table 5.

Table 5. The mean and standard deviation of the ratio comparison of bearing capacity calculations for Q_{ult}.

Ratio Q_{ult} Empirical Methods/Measured			
Test	Model	Mean Value	Deviation Standard
	I	0.889	0.159
PDA	II	1.021	0.198
	III	0.973	0.170
	I	0.744	0.186
SLT	II	0.880	0.250
	III	0.829	0.220

I = Kulhawy Method (1984)
II = Reese & Wright (1977)
III = Reese & O'Neil (1988)

From the comparison calculations for the ultimate bearing capacity in each calculation method, it is known that the mean values range from 0.7 to 1. Statistical criteria based on the mean values can be considered well when the value is approaching 1, indicating a smaller error between the compared data. The calculation method with the mean value closest to value '1' is Reese & Wright's adhesion factor method (1977) with mean values of 1.021 for PDA and 0.880 for SLT.

Meanwhile, the standard deviation values range from 0.1 to 0.3. Statistical criteria based on the standard deviation values can be considered well when approaching a value of 0, indicating a smaller deviation between the measured data points from the mean value within a range. The adhesion factor method with the standard deviation value closest to 0 is Kulhawy's method (1984) with standard deviation values of 0.159 for PDA and 0.186 for SLT.

Based on the comparison of empirical axial bearing capacity calculation data for bored piles with field test data obtained from Static Loading Test and Pile Driving Analyzer, recommendations for the axial bearing capacity calculation method will be determined. Iterative process and stages were carried out to obtain coefficient factors for the cu, fs for sand, and q_p for sand calculation models for each adhesion factor method, resulting in the following outcomes shown by Table 6, Table 7, and Table 8. Each table provide a comparison of data plot and their "best-fit" line when using the empirical calculation method with coefficients consist of c_u = 6N, f_s for sand = 2N, and q_p for sand = 70 N to the recommended method that was obtained.

Table 6. Comparison of recommended methods and empirical calculations using Kulhawy's adhesion factor (1984)

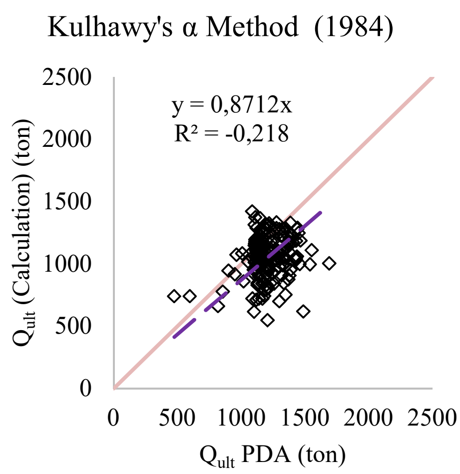
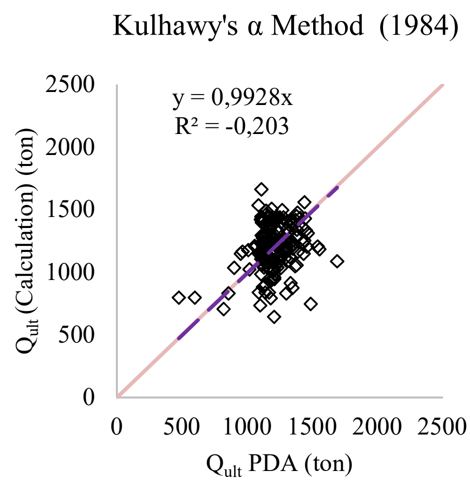
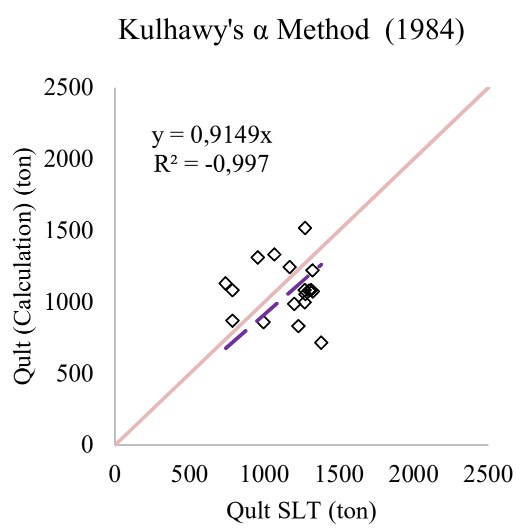
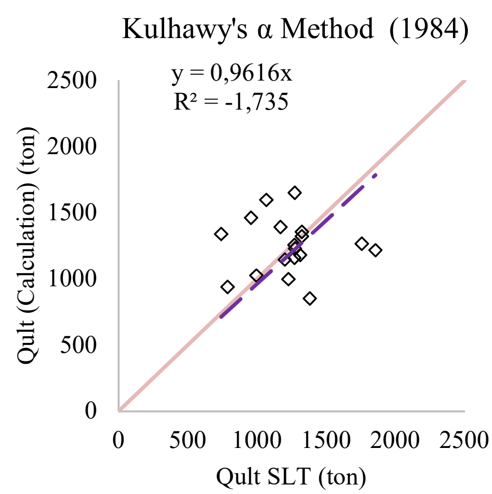
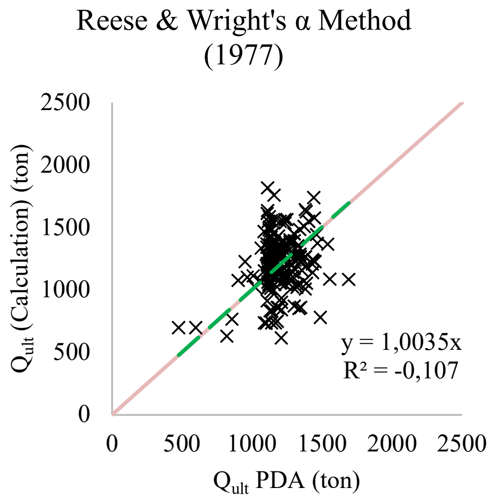
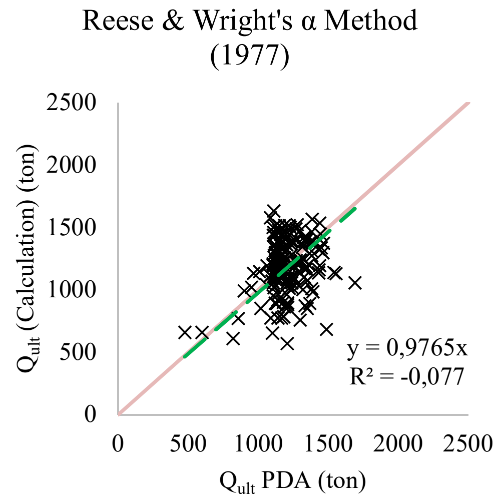
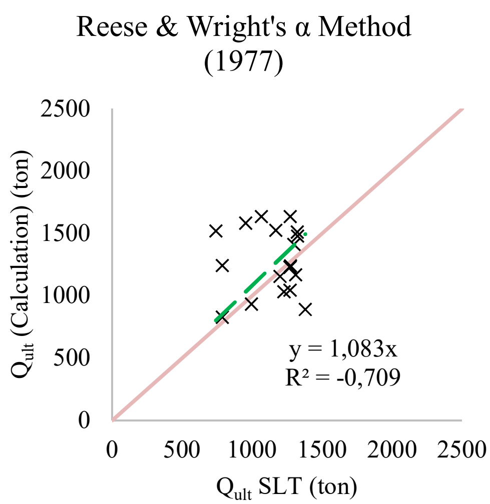
Kulhawy's Adhesion Factor (1984), c_u = 8 N, f_s for sand = 2.2 N, and q_p for sand = 70 N	
Empirical	Recommendation
	
	

Table 7. Comparison of recommended methods and empirical calculations with Reese & Wright's adhesion factor (1977)

Reese & Wright's Adhesion Factor (1977), c_u = 5 N, f_s for sand = 2.5 N, dan q_p for sand = 60 N	
Empirical	Recommendation







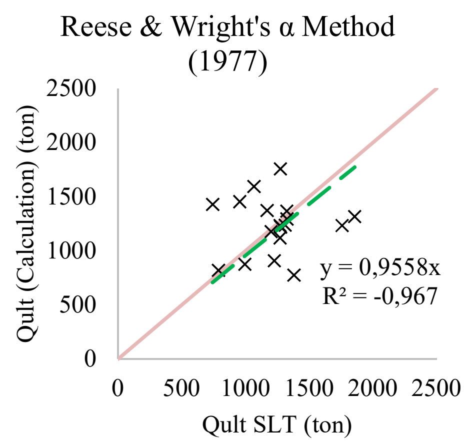
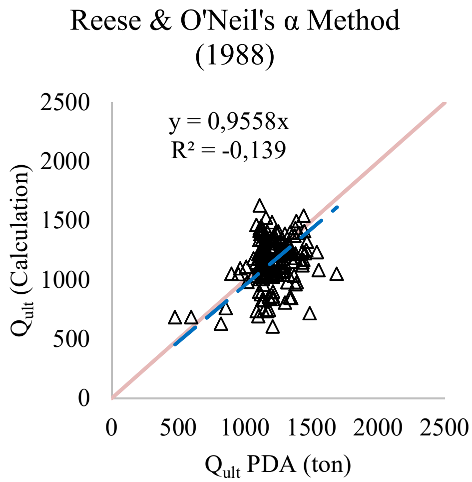
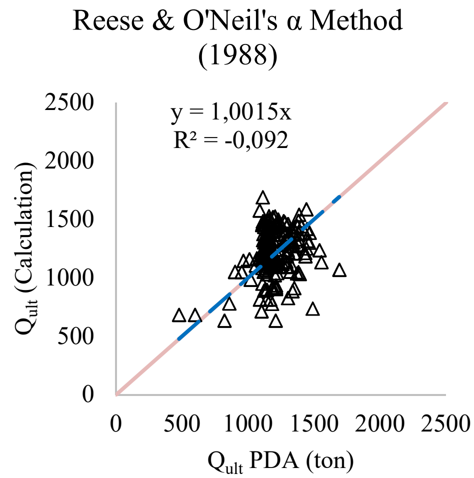
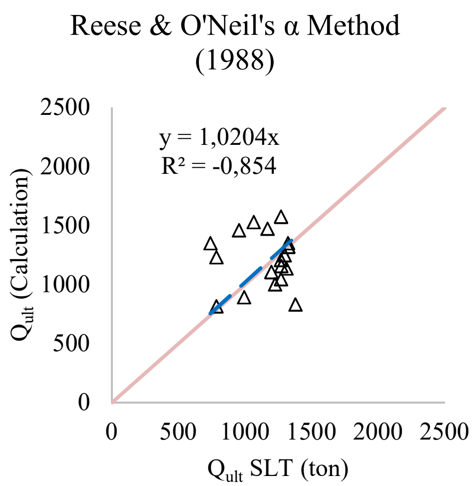
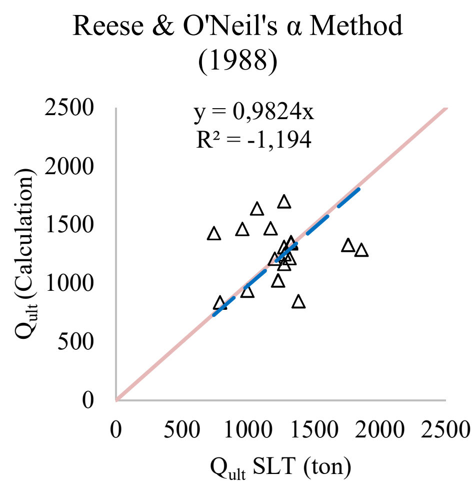


Table 8. Comparison of recommended methods and empirical calculations with Reese & O'Neil's adhesion factor (1988)

Reese & O'Neil's Adhesion Factor (1988), c_u = 6N, f_s for sand = 2.4 N, dan q_p for sand = 60 N	
Empirical	Recommendation
	
	

From Table 6, Table 7 and Table 8, the best correlation to be used for each method can be determined. Since all three methods provide average values within the similar range, which is 0.8-1.1, they will be then compared to the R^2 values of the ultimate resistance provided. As a result, it was found that the best correlation to be used is c_u = 8 N, f_s for sand = 2.2 NSPT, and q_p for sand = 70 N while using Kulhawy (1984) for adhesion factor method.

5 CONCLUSION

Back Calculations were performed to determine the model for calculating the axial bearing capacity of the foundation using field measurement data. It was found that for the West Java Toll Road construction project, it is recommended to use Kulhawy's adhesion factor model (1984) with correlation values of $c_u = 8\ N_{SPT}$, f_s for sand = $2.2\ N_{SPT}$, and q_p for sand = $70\ N_{SPT\text{-}ave}$. This comparison was made by evaluating statistical criteria, including the coefficient of determination, mean value, and standard deviation of the recommended axial bearing capacity calculation model and the field measurements.

However, it should be noted that the comparison results show a uniformity that leads to large R^2 values. This could be caused by the limited variation of bored piles at the project site. Therefore, it is suggested that the model formulated in this study is site-specific and recommended for use in locations with similar soil data.

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