The application of cone penetration test direct method in Jakarta

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Abstract. There are several methods to estimate the bearing capacity of pile foundation using cone penetration test (CPT). Hence, it is interesting to evaluate which method that suitable for a certain location. In this study, 55 piles histories in Jakarta, which consisted of bored piles and driven piles, are used in order to determine the bearing capacity using the following methods: Schmertmann, de Ruiter and Beringen, LCPC, Aoki and De Alencar, Penpile, Price and Wardle, Philipponnat, and Wesley. The pile capacities will be compared to the measured pile capacities from the bearing capacity from loading test: static pile load test which interpreted by Chin method and Decourt method, and the results from PDA testing. The statistical analyses used in this paper are the best fit line, mean and standard deviation, and log distribution with 20% of accuracy. Result shows that LCPC method is the most suitable direct method used in studied location as it has the best agreement among the methods mentioned; the cone penetration test direct method is more suitable used for driven pile; and the safety factor for Chin and Decourt loading test interpretation methods are 2.7 and 2.57 respectively according to Wesley direct method.

1. Introduction
Pile foundations are designed to transfer the loads from the structures to the soil. Thus, it is vital for the pile foundation to have bearing capacity which adequates the load above so the settlement of the soil will not occur or can be minimized. One of the calculations which can be used to determine the pile foundation’s bearing capacity is direct method, that is varied. In this method, the calculation is done using in situ test data. In situ test that is commonly used is the cone penetration test (CPT) which provides the data of considered location soil that can be used to classify the soil type and to determine the bearing capacity of pile foundation.

In this study, 55 piles data histories which are obtained from 9 different locations in Jakarta, which consisted of bored piles and driven piles, are used to determine the pile bearing capacity and denoted with \( Q_p \). The following CPT direct methods used are Schmertmann, De Ruiter and Beringen, LCPC, Aoki and De Alencar, Penpile, Price and Wardle, Philipponnat, and Wesley. Due to the variosity of the CPT direct methods, evaluation is needed in order to find out which method is the closest to the actual condition on the field. The actual condition is the ultimate load capacity of the pile obtained from loading test, denoted with \( Q_m \). The loading test mentioned are the static load test that was determined using the Chin method and Decourt method, and some from the result of PDA testing. Wesley method is not included in comparison between \( Q_p \) and \( Q_m \).
2. Research Methodology

Pile Characteristics

55 piles are used in order to determine the ultimate capacity using CPT direct methods mentioned. The piles consisted of 26 bored piles and 29 driven piles. The length of bored piles varied from 19.05 m to 53.2 m and the diameter varies from 0.8 to 1.2 m. Meanwhile the length of driven piles varied from 16 m to 39 m and the side length varied from 0.4 m to 0.5 m.

Soil Classification

The cone penetration test provides the soil data such as the cone tip resistance ($q_c$), sleeve friction ($f_s$), total friction, and friction ratio (FR). It is important to classify the soil type when using CPT direct methods in order to use the correct factors according to each method. In this study, the method used for classifying soil types utilizing CPT data is Robertson et al (1986), which classifies soil types based on the Friction Ratio (FR) and the cone bearing ($q_c$).

![Figure 1. Soil Classification according to Robertson et al. (1986).](image)

Information:
1. Sensitive fine-grained soil
2. Organic soil
3. Clay
4. Silty clay to clay
5. Clayey silt to silty clay
6. Sandy silt to clayey silt
7. Silty sand to sandy silty
8. Sand to silty sand
9. Sand
10. Sand to gravelly sand
11. Very stiff fine-grained soil
12. Overconsolidated or cemented sand to clay

Load Test

The ultimate capacity of pile from the actual site is obtained by loading test. The loading test mentioned are from PDA testing and axial loading test, which interpreted by the Chin method and Decourt method, because 55 piles used for this study were not failed under loading test. Therefore, the Chin method and the Decourt method used to extrapolate the ultimate capacity. The value that were used for comparison is the mean obtained from both methods.

Cone Penetration Test Direct Method

The ultimate bearing capacity ($Q_u$) consisted of the end-bearing capacity ($Q_b$) and the shaft friction capacity ($Q_s$). The equation in general is given by

$$Q_u = Q_b + Q_s = A_b q_b + \sum_{i=1}^{n} f_i A_s i$$

where $Q_b$ is the end-bearing capacity, $A_b$ is the cross-section area of the pile, $q_b$ is the value of cone tip resistance (kg/cm²), $Q_s$ is the shaft friction capacity, $f_i$ is the sleeve friction (kg/cm²), $A_s i$ is the pile shaft area interfacing with layer $i$, and $n$ is the number of soil layers along the pile shaft. The cone penetration methods used in this study for comparison with the ultimate bearing capacity from loading test are given by
Table 1. CPT Direct Methods

| CPT Direct Method          | $q_b$                                      | $f$                                      |
|----------------------------|-------------------------------------------|------------------------------------------|
| LCPC                       | $q_b = k_{b1} q_c$                         | $f = C \cdot q_c$                        |
|                           | $k_{b1} = 0.15-0.60$ depending on soil    |                                          |
|                           | type and installation of pile             |                                          |
|                           | $q_c = \text{average of } q_c \text{ values of zone}$ |                                          |
|                           | ranging from 1.5D below pile tip to       |                                          |
|                           | 1.5 above pile tip                        |                                          |
| Penpile                    | $q_b \begin{cases} 0.25 q_c & \text{pile tip in clay} \\ 0.125 q_c & \text{pile tip in sand} \end{cases}$ | $f = \left( \frac{f_s}{1.5+0.1 f_s} \right)$ |
|                           |                                          | $f_s \text{ and } f \text{ in psi}$       |
| Price and Wardle           | $q_b = k_{b2} q_c$                         | $f = k_{s1} f_s$                         |
|                           | $k_{b2}$ depending on the pile type,      |                                          |
|                           | 0.35 for driven piles, 0.3 for jacked     |                                          |
|                           | piles                                    |                                          |
| Philipponnat               | $q_b = k_{b3} q_c a$                      | $f = \frac{\alpha_s}{F_s} q_c s$         |
|                           | $q_{ca} = \frac{q_{ca (A)} + q_{ca (B)}}{2}$ |                                          |
|                           | $q_{ca (A)} = \text{average of } q_c \text{ values 3D}$ |                                          |
|                           | above pile tip                           |                                          |
|                           | $q_{ca (B)} = \text{average of } q_c \text{ values 3D}$ |                                          |
|                           | below pile tip                           |                                          |
|                           | $k_{b3} = 0.35 - 0.5$ depending on soil  |                                          |
|                           | type                                     |                                          |
| Aoki De Alencar            | $q_b = \left( \frac{q_{real (tip)}}{F_b} \right) \leq 15 \text{ MPa}$ | $f = q_c \frac{\alpha_s}{F_s} \leq 120 \text{ kPa}$ |
|                           | $F_b = 1.75 - 3.5$ depending on the      |                                          |
|                           | pile type                                |                                          |
| De Ruiter and Beringen     | $q_b = (Nc \frac{q_c (tip)}{N_k}, \text{clay} \leq 15 \text{ MPa}$ | $f = (\beta \frac{q_c (tip)}{N_k})$, clay \leq 120 \text{ kPa}$ |
|                           | In sand (similar to Schmertmann)         |                                          |
|                           | $N_c = 9$                                |                                          |
|                           | $N_k = 15-20$                            |                                          |
| Schmertmann                | $q_b = \frac{q_{c1} + q_{c2}}{2} \leq 15 \text{ MPa}$ | $f = k_{s2} f_s$, clay \leq 120 \text{ kPa}$ |
|                           |                                          | $f = K_c \cdot q_c$, sand                |
|                           | $q_{c1} = \text{average of } q_c \text{ values of zone}$ |                                          |
|                           | ranging from 0.7 to 4D below the         |                                          |
|                           | pile tip                                 |                                          |
|                           | $q_{c2} = \text{average of } q_c \text{ values 8D}$ |                                          |
|                           | below pile tip                           |                                          |
|                           | $k_{s2} = 0.2-1.25$ for clay              |                                          |
|                           | $K_c = 0.008$ for open-end steel tube     |                                          |
|                           | piles, 0.012 for precast concrete and     |                                          |
|                           | steel displacement pile, 0.018 for        |                                          |
|                           | vibro and cast-in-place displacement      |                                          |
|                           | piles with steel driving tube removed and |                                          |
|                           | timber piles                             |                                          |
Wesley method is exclude from the comparison between the ultimate bearing capacity obtained from CPT direct method calculation \( (Q_p) \) and the ultimate bearing capacity from loading test \( (Q_m) \), because the bearing capacity value has been divided by safety factor (SF), resulting in allowable bearing capacity \( (Q_{all}) \). As for Wesley method, it is used to determine the safety factor that can be used for the interpretation load test as mentioned, Chin method and Decourt method. Wesley method is given by

\[
Q_{all} = \frac{q_b A_b}{3} + \frac{f_s A_s}{5}
\]

where 3 and 5 are safety factors.

3. Results of Analyses

All Pile Analyses

The best-fit line analyses, where \( Q_p \) is plotted on x-axis meanwhile \( Q_m \) is plotted on y-axis, and the coefficient determination \( (R^2) \) of each CPT method is shown in Figure 4. The dotted line is the perfect fit line. Based on the best-fit line analyses, LCPC method shows the best match \( (R1=1) \) as the \( Q_m/Q_p \) ratio is \( y = 0.93x \) \( (R^2=0.48) \), the closest to one. The equation shows that LCPC method is overpredicted because the measured bearing capacity have smaller values than the predicted capacity. The CPT direct method that is the closest to one, the ideal condition, based on the mean and standard deviation of \( Q_p/Q_m \) ratio is Philipponnat, 1.05 showing a slight overprediction by 5\% \( (R2=1) \). The last analyses is the log normal distribution with the level accuracy of 20\% which is shown in Figure 5. A level accuracy of 20\% indicates that the predicted ultimate bearing capacity \( (Q_p) \) is within the range 0.8\( Q_m \) and 1.2\( Q_m \). The log normal distribution is defined with the following probability density function:

\[
f(x) = \frac{1}{\sqrt{2\pi}\sigma \ln x} \exp \left[ -\frac{1}{2} \left( \frac{\ln(x) - \mu_{\ln}}{\sigma_{\ln}} \right)^2 \right]
\]

The data shows that Philipponnat shows the best performance with \( P_{20\%} = 88.61\% \) \( (R3=1) \).

Rank Index (RI) was used to conclude the overall performance of each CPT method, presented in Table 2. The rank index is defined as the sum of the ranks from the different criteria \( (RI = R1+R2+R3) \). The lower the rank index is, the better the performance of the method. According to the Rank Index (RI), LCPC method has the best agreements among the seven methods mentioned with \( R1=1, R2=2, \) and \( R3=2, \) there for the \( RI = 5 \) \( (R1 = R1+R2+R3) \).

![Figure 2. The Best-Fit Line Analyses Result](image-url)
Based on pile type

3.1.1. Bored piles. According to the first analyses, the best-fit line, LCPC method shows the best match with a slight of overprediction with \( Q_m/Q_p \) ratio is \( y = 0.92x \) (\( R^2 = 0.19 \)). Therefore, this method is given \( R1 = 1 \). Then, the second analyses, mean and standard deviation, the data shows that LCPC method shows that it is the closest to the ideal condition with an overprediction by 14% (\( R2 = 1 \)). The last analyses, shows that Price and Wardle has the best probability with \( P_{20\%} = 48.88\% \) (\( R3 = 1 \)).

According to the RI evaluation, it shows that LCPC has the best performance among the seven methods compared.
3.1.2. Driven Piles. According to the first analyses, the best-fit line, LCPC method shows the best match with a slight of overprediction with \( Q_m/Q_f \) ratio is \( y = 1.02x \) \((R^2 =0.11)\). Therefore, this method is given \( R_1=1 \). Then, the second analyses, mean and standard deviation, the data shows that Aoki de Alencar shows that it is the closest to the ideal condition with an underprediction by 8\% \((R^2=1)\). The last analyses, shows that Aoki de Alencar has the best probability with \( P_{20\%} = 68.77\% \) \((R^3=1)\). According to the RI evaluation, it shows that Aoki de Alencar has the best performance among the seven methods compared.
According to the analyses, LCPC method shows a consistency of a low value of rank based on Rank Index, indicating the method has a great performance. The Rank Index based on the bored piles analyses is 4 and from the driven piles analysis the RI is 7.

The depth of cone penetration test done in the location determines the accuracy of the ultimate bearing capacity calculated by cone penetration direct method as the value of cone tip resistance ($q_t$) and sleeve friction ($f_s$) are used in the calculation. If the depth of the CPT does not adequate the length of the pile, meaning the pile foundation is deeper than the data of CPT, then it is assumed to be the hard layer of the soil with the value of $q_t$ and $f_s$ are 15 MPa and 120 kPa respectively. This problem occurred in bored pile data calculations, as bored piles are deeper than driven piles. Based on the best-fit line data, it is shown that the data resulted from bored pile calculations are more scattered than the data from driven pile calculations. This might be caused by the uncertainty given by the assumption. Therefore, it can be concluded that the calculation of CPT direct method is more suitable for driven piles because of the limitation depth of CPT and the driven pile length which is not as deep as bored piles.

Safety Factor of Interpretation Loading Test Method based on Wesley Method

The value of the safety factor (SF) for the loading test interpretation method is obtained by dividing the value of measured capacity, Chin and Decourt, with the allowable bearing capacity resulting from Wesley method calculation. The formula is given by

$$SF_1 = \frac{Q_m}{Q_p} \quad (4)$$

![Figure 7. The Log Normal Distribution 20% Accuracy for Driven Piles](image)

| Direct Method | Best-Fit Line | Mean and Standard Deviation | Log Distribusi Normal | Rank Index RI |
|---------------|---------------|----------------------------|-----------------------|---------------|
|               | $Q_m/Q_{fit}$ | $Q_{fit}/Q_m$ | $R^2$ | $R_1$ | $Mean$ | $SD$ | $R_2$ | $20\%$ accuracy level | $R_3$ | Rank |
| LCPC          | 1.02          | 0.98          | 0.11 | 1     | 1.1  | 1.04 | 2     | 32.34 | 4     | 7   | 2    |
| Penpile       | 1.25          | 0.80          | 0.11 | 4     | 0.88 | 0.35 | 3     | 28.02 | 5     | 12  | 4    |
| Price and Wardle | 1.47          | 0.68          | 0.10 | 7     | 0.75 | 0.27 | 4     | 9.36  | 7     | 18  | 6    |
| Philipponnat  | 0.81          | 1.23          | 0.04 | 5     | 1.34 | 0.65 | 6     | 54.66 | 2     | 13  | 5    |
| Aoki De Alencar | 1.24         | 0.81          | 0.15 | 3     | 0.92 | 0.37 | 1     | 68.77 | 1     | 5   | 1    |
| De Ruiter and Beringen | 0.76       | 1.31          | 0.11 | 6     | 1.44 | 0.54 | 7     | 17.74 | 6     | 19  | 7    |
| Schmertmann   | 0.86          | 1.17          | 0.15 | 2     | 1.31 | 0.48 | 5     | 48.21 | 3     | 10  | 3    |

Table 4. Performance of CPT Direct Method According To Rank Index
After the value of SF of each pile has been obtained, then all 55 SF obtained from each pile are added up. The overall SF is determined by dividing the SF that has been added up, with the number of pile which is 55. The result shows that the safety factor for Chin and Decourt loading test interpretation methods are 2.7 and 2.57 respectively. SF is needed as the bearing capacity from loading test is an ultimate bearing capacity, meaning the value has not been divided by SF. By having safety factors, the allowable bearing capacity can be known thus the values can be compared to the allowable bearing capacity resulting from Wesley method calculation.

4. Conclusions
The ultimate bearing capacity of pile foundation can be determined using CPT direct methods. This study used the following CPT direct methods: Schmertmann, De Ruiter and Beringen, LCPC, Aoki De Alencar, Penpile, Price and Wardle, Philipponnat, and Wesley. 55 piles histories in Jakarta, which consisted of bored piles and driven piles, are used. The result from CPT direct method and the ultimate bearing capacity from loading test, PDA testing and axial load test which interpreted by Chin and Decourt method, are compared and analyzed. Three statistical analysis used in this paper are the best-fit line equation, mean and standard deviation, and log normal distribution with an accuracy level of 20%. The results show that LCPC has the best agreements and is the most favorable method to be used in the studied location as the result shows that the ultimate bearing capacity resulted by this method are the closest to the ultimate bearing capacity measured by loading test and that the CPT direct method is more suitable for driven pile. The safety factors for Chin method and Decourt method are 2.7 and 2.57 respectively.

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