Comparison of ultimate bearing capacity based on empirical method, interpretation of loading pile test and finite element

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Abstract. Civil Engineers in designing the ultimate bearing capacity of the pile usually uses several empirical methods. Then usually the loading pile test will be conducted to confirm the ultimate carrying capacity in the field. Based on conditions that often occurs in the field, an empirical method of research is carried out to find out which method is closest to results of the field test. So that in designing the ultimate bearing capacity of the deep foundation will be closer to the field conditions. The empirical methods used in this case are the method of Bazara and Luciano Decourt, while the interpretation of filed results uses the methods of Chin, Mazurkiewiz and Lastiasih. Based on the results of empirical methods and interpretation of the ultimate bearing capacity of the field test, the results of the pile loading test will be analysed using finite element. The result of this research shows Finite Element method, Luciono Decourt and Lastiasih are the closest produce produce ultimate bearing capacity with loading pile test until failure.

1. Introduction

Recently, the construction of high rise buildings has strict requirements, especially related to the planning of the foundation. All building plans in Jakarta must carry out loading pile tests as one of the requirements in carrying out foundation work. Planning in several areas of the big city has also begun to use loading pile test requirements. The problem that is often encountered in the field is the result of the interpretation of the ultimate bearing capacity of the loading pile test in the field that is not comfortable with empirical theories or finite element-based support programs. Therefore, the author will discuss the ultimate bearing capacity of each method, so it can be concluded which method is the closest to the results of the field test pile. Several studies have conducted numerical analysis to compare the results of interpretation of field test piles and see the relationship between soil and piles as has been done by KRASIńSKI[1], Zein [2] and Lastiasih [3].

KRASIńSKI, et al [1] conducted numerical analysis for piles with a diameter of 1500 m with length \( L = 19.7 \) m, where the results of the load distribution on the pile can be seen in figure 1. The numerical analysis results showed that around 81% of the total load was received by friction bearing capacity and 19% held by the base bearing capacity of pile, while the field test results show that the total load received by pile is 68% received by friction bearing capacity and 32% is held by the base bearing capacity of pile.
Zei et al. [2] present an evaluation of the bearing capacity of bored pile which is measured directly and obtained from the interpretation method of selected load test data based on different failure criteria. Zein [2] conducted an experiment on a field scale, which was to install a bored pile in alluvial soil deposits and load by static load until it failure. The measured failure load varies from 195 to 520 kN and pile movements of 1.3 to 2.7% D are needed to mobilize the load at the time of testing. The friction bearing capacity contributes more than 83% of the total bearing capacity and is mobilized when the movement is 0.2 to 0.8% D. Total load receive by the friction bearing capacity 83%. These result indicate that the quantity is almost same ast the experiment from KRASiNSKI [1]. Zein [2] also interpreted the results of the loading test using several methods. As for the results obtained for the Fuller and Hoy methods show the best overall performance in estimating the ultimate load, the De Beer and Van der Veen methods produce a good evaluation while the Davisson interpretation method shows relatively poor results. The method that produces the highest ultimate carrying capacity estimate among the methods used by Zein [2] is Chin. The results of Zein et al [2] are in line with the results from Lastiasih et al [3]. Lastiasih [3] compared the Chin [4] method with Mazurkiewicz [5], Brinch Hansen [6] and Van der Veen [7] and obtained the highest estimate ultimate bearing capacity with Chin method. But Lastiasih also interpreted using the Decourt Extrapolation [8] method, and when compared with the Chin [4] method it turned out that the highest Decourt Extrapolation [8] method produced the ultimate carrying capacity.

Existing interpretation methods also still produce varying values, so Kaniraj [9] and Lastiasih [3] try to develop new interpretation methods. The ultimate bearing capacity interpretation method based on the results of the pile test in the form of a load-settlement curve that has been mathematically extrapolated was also developed by Kaniraj [9] as a hyperbolic equation. This concept has been effectively used to estimate the ultimate carrying capacity of large diameter piles in several projects (Sanjay Gupta & Ravi Sundaram, [10]). The equation used for the hyperbolic model is as follows:

\[ S' = a + bS' \]

Where :

- \( S' = s/D \) s = settlement
- \( D \) = Pile diameter
- \( Q' = Q/Qr \) Q = Applied Load
- \( Qr \) = Reference Load
- \( a \) and \( b \) are constants determined from a linear regression analysis of \( S'/Q' \) and \( S' \).

In addition to the formula developed by Kaniraj [9]., Lastiasih [3] also established a formula to interpret the ultimate carrying capacity with quadratic hyperbolic, using the following equation:
Where:

\[
Q = \frac{a(x^2 + bx)}{x^2 + cx + d}
\]  

(2)

Kaniraj [9] and Lastiasih [3] used hyperbolic equations as an effort to estimate the ultimate bearing capacity based on the results shown in the load vs. decrease curve. The results obtained show a hyperbolic shape for both single pile and group pile according to Eurocode 7 [11], as seen in figures 2 and 3.

![Figure 2. Load-settlement curves for single piles and group piles [11]](image1)

![Figure 3. Schematic diagram to determine the Q-s characteristics of the "i" pile in a group [11]](image2)

Based on existing conditions in the field that the results of several previous researchers who produced a different reality between the results of field testing and the results of the ultimate bearing capacity calculation interpretation, the researchers tried to compare the ultimate bearing capacity of interpretant results with empirical theories and finite elements, to determine which method was more appropriate to use. The empirical method used is Luciano Decourt and Meyerhoff Bazara, because the average projects are using that method. Likewise, the selection of interpretation methods with Chin was also carried out in many projects, and 2 other methods were chosen namely Mazurkiwiz and quadratic hyperbolic from Lastiasih.

2. Research data

This study uses data from loading pile test results, and soil test results data in one of the projects in the Dharmawangsa Jakarta area, where the piles tested with a diameter of 100 cm in 5 locations. Pile data, depth, and ultimate load tested on the pile can be seen in table 1

| Pile location | \( \phi \) | \( L \) | Quilt load test |
|---------------|-----------|-------|----------------|
| BP98          | 30        |       | 1200           |
| BP145         | 26,03     |       | 700            |
| BP190(F)      | 1         | 24,97 | 700            |
| BP334         | 25,77     |       | 800            |
| BP355 (F)     | 24,32     |       | 265,625        |
Soil data of 3 points in the research location are dominated by clayey silt layers, as shown in table 2 to table 4.

### Table 2 Soil parameters BH 1

| Depth (m) | Soil consistency | N_SPT | Cu (t/m²) | \( \gamma_{sat} \) (t/m³) | E (Mpa) | \( \nu \) | \( \phi \) |
|-----------|-----------------|-------|-----------|--------------------------|---------|------|------|
| 0,00 - 6,50 | Silty Clay | 7,00  | 4,20 | 1,66 | 7,20 | 0,20 | 12,60 |
| 6,50 - 13,50 | Silty Clay | 15,00 | 9,00 | 1,68 | 12,00 | 0,30 | 27,00 |
| 13,50 - 15,00 | Sandy silt | 24,00 | 14,40 | 1,96 | 17,40 | 0,35 | 30,00 |
| 15,00 - 21,00 | Clayey silt | 30,50 | 18,30 | 2,00 | 21,30 | 0,30 | 30,00 |
| 21,00 - 27,50 | Sand | 37,50 | 0,00 | 1,75 | 25,50 | 0,35 | 35,26 |
| 27,50 - 29,00 | Clayey silt | 37,50 | 22,50 | 2,00 | 25,50 | 0,33 | 30,00 |
| 29,00 - 32,50 | Sandy silt | 37,50 | 22,50 | 2,00 | 25,50 | 0,30 | 30,00 |
| 32,50 - 36,50 | Clayey silt | 37,50 | 22,50 | 2,00 | 25,50 | 0,33 | 30,00 |
| 36,50 - 40,50 | Silty sand | 30,00 | 0,00 | 1,75 | 21,00 | 0,30 | 35,26 |
| 40,50 - 45,00 | Clayey silt | 23,75 | 14,25 | 1,93 | 17,25 | 0,30 | 30,00 |
| 45,00 - 51,50 | Sandy silt | 29,33 | 17,60 | 2,00 | 20,60 | 0,35 | 30,00 |
| 51,50 - 57,50 | Sand | 37,50 | 0,00 | 1,75 | 25,50 | 0,38 | 35,26 |
| 57,50 - 58,50 | Silty sand | 37,50 | 0,00 | 1,75 | 25,50 | 0,30 | 35,26 |
| 58,50 - 60,50 | Clayey silt | 37,50 | 22,50 | 2,00 | 25,50 | 0,35 | 30,00 |

### Table 3 Soil parameters BH-2

| Depth (m) | Soil consistency | N_SPT | Cu (t/m²) | \( \gamma_{sat} \) (t/m³) | E (Mpa) | \( \nu \) | \( \phi \) |
|-----------|-----------------|-------|-----------|--------------------------|---------|------|------|
| 0,00 - 5,50 | Silty Clay | 2,33  | 1,40 | 1,53 | 4,40 | 0,20 | 4,20 |
| 5,50 - 9,50 | Clayey silt | 10,50 | 6,30 | 1,70 | 9,30 | 0,30 | 18,90 |
| 9,50 - 15,50 | Clayey silt | 37,50 | 16,03 | 1,75 | 25,50 | 0,35 | 30,00 |
| 15,50 - 21,50 | Sand | 37,50 | 0,00 | 1,75 | 25,50 | 0,38 | 35,26 |
| 21,50 - 37,00 | Sandy silt | 37,50 | 22,50 | 2,00 | 25,50 | 0,35 | 30,00 |
| 37,00 - 47,00 | Clayey silt | 18,25 | 10,95 | 1,71 | 13,95 | 0,33 | 30,00 |
| 47,00 - 52,50 | Sand | 31,33 | 11,30 | 1,92 | 21,80 | 0,30 | 30,00 |
| 52,50 - 60,50 | Clayey silt | 27,50 | 19,50 | 2,00 | 19,50 | 0,35 | 30,00 |
Table 4 Soil parameters BH-3

| Depth (m) | Soil consistency | N$_{SPT}$ | Cu (t/m$^2$) | $\gamma_{sat}$ (t/m$^3$) | E (Mpa) | v | $\phi$ |
|-----------|------------------|-----------|--------------|-------------------|--------|---|-------|
| 0,00 - 11,50 | Silty Clay | 3,50 | 2,10 | 1,64 | 5,10 | 0,30 | 6,30 |
| 11,50 - 14,50 | Clayey silt | 10,50 | 6,30 | 1,70 | 9,30 | 0,30 | 18,90 |
| 14,50 - 35,50 | Sand | 37,40 | 0,00 | 1,74 | 25,44 | 0,38 | 35,22 |
| 35,50 - 37,50 | Sandy silt | 19,00 | 12,20 | 1,73 | 14,40 | 0,35 | 30,00 |
| 37,50 - 43,50 | Clayey silt | 27,33 | 16,40 | 1,87 | 19,40 | 0,35 | 30,00 |
| 43,50 - 55,50 | Sand | 34,17 | 0,00 | 1,71 | 23,50 | 0,33 | 34,63 |
| 55,50 - 60,50 | Clayey silt | 21,33 | 12,80 | 1,85 | 15,80 | 0,30 | 30,00 |

The soil data are used for modeling on plaxis and input phisik parameter to calculated ultimate bearing capacity by Luciano Decourt and Meyerhof Bazara. The soil data is used to find the ultimate carrying capacity with diameter and depth according to the pile test in the field as seen in table 5

Table 5 Location soil test and loading pile test

| Location Loading Pile Test | Location Soil Test |
|----------------------------|--------------------|
| BP98                       | BH-1               |
| BP145                      | BH-2               |
| BP190(F)                   | BH-3               |
| BP334                      | BH-1               |
| BP355 (F)                  | BH-1               |

3. Calculation Method
The interpretation method used in this study is the method of Chin [4], Mazurkiewicz [5], Lastiasih [3], while the empirical method used is the Luciano Decourt [12] method and Meyerhof-Bazara method [13][14]

3.1. Chin Method (1971)
The procedure to determine the ultimate load using this method is as follows:
- Figure $s / Q$ for $s$, where $s$ is a settlement, and $Q$ is the load applied.
- Ultimate load ($Q_{\text{ult}} = 1 / C1$).
3.2. Mazurkiewicz Method

The steps to find the ultimate carrying capacity of the results of the load settlement curve using the Mazurkiewicz method are as follows:

Plot the load-settlement curve, select the amount of settlement value in the curve and draw a vertical line that intersects the curve. Then draw a horizontal line from this point of intersection on the curve until it intersects the load axis. From the intersection of each curve, draw a 45° line to cut the next load line. The intersection is approximately located on a straight line. The point obtained by the intersection of this line extension on the vertical axis (load) is the ultimate load.
3.3. **Quadratic Hyperbolic Method** [3]
As seen in Eq.2 where to get constants a, b and c can be done using the help of the MatLab program.

3.4. **Luciano Decourt Method** [12]
Luciano Decourt Method is valid for all soil types (cohesive & non-cohesive), the pure data input from Nspt value.

\[ Q_p = \alpha q_p \times A_p = \beta (\bar{N}_p \times K) \times A_p \] \hspace{1cm} (3)

where:
- \( q_p \): stress on based foundation in t/m²
- \( A_p \): Sectional area of the base foundation, \( \alpha \): base coefficient = 1 (driven pile)
- \( \bar{N}_p \): The average of Nspt around 4B above until 4B below the base of pile foundation (B = Pile diameter) = \( \sum_{i=1}^{n} N_i \)
- \( K \): coefficient of characteristic soil: 12 t/m² for clay; 20 t/m² for clayey silt; 25 t/m² for sandy silt; 40 t/m² for sand

\[ Q_s = \beta \times q_s \times A_s = \beta (\bar{N}_s/3 + 1) \times A_s \] \hspace{1cm} (4)

where:
- \( q_s \): friction stress in t/m²
- \( \bar{N}_s \): The average of Nspt along foundations are embedded, with restrictions: 3 < N < 50
- \( A_p \): Circumference x length foundation which sets, \( \beta \): shaft coefficient = 1

3.5. **Meyerhoff-Bazara Method** [14][13]
Bearing capacity by Meyerhoff Bazara follows the equation below:

\[ P_{ult} = C_r A_{base} + \sum_{i} C_i A_i \text{ or } P_{ult} = 40 \bar{N} A_{base} + \sum_{i} \frac{N_i}{20.5} \times A_i \] \hspace{1cm} (5)

Where:
- \( C_i \): resistance of friction pile at segment \( i = fsi \)
- \( A_i \): friction area of segment \( i = O_i \times h_i \)
- \( O_i \): perimeter of pile
- \( \bar{N} \): The average of N2, 4D along the end of the pile down s/d 8D along the end of the pile to the top

\[ N_1 = 15 + \frac{1}{2}(N - 15) \text{ or } N_1 = 0,6N \] \hspace{1cm} (6)

\[ N_2 = \frac{4N_i}{1 + 0,4\sigma_o} \] \hspace{1cm} (7)

\[ N_2 = \frac{4N_i}{3,25 + 0,1\sigma_o} \] \hspace{1cm} (8)

3.6. **Finite Element Method**
The Finite Element Method (FEM) is a method of approximation the behavior of continua. In this numerical technique the system is discretized into many meshes or element, then the equability and compatibility of each element, and whole system will be examined. In geotechnical engineering, PLAXIS is one of the most widely used finite element softwares. To model the pile used in this study into PLAXIS 2D, a work area with a width of 50 m and a depth of 60.5 m was used and the geometry was simulated using the axisymmetric model in which the pile was positioned along the axis of symmetry. With the aid of standard fixation boundary conditions, concrete piles with a total length vary
according to table 1 modeled. The pile has a diameter of 1.0 m; then it is defined as a column with a width of 0.5 m. Both the soil and the piles are modeled with 15-node elements.

![Figure 6. Modelling FEM](image)

4. Result and Analysis

Based on the results of interpretation using the Chin [4], Mazurkewicz [5], Lastiasih [3], Finite Element methods and on the results of loading pile test results are obtained as follows:

| Pile Location | The pile load test | Loading Pile Test interpretation methods result | The pile bearing capacity using empirical methods | Finite Element |
|---------------|--------------------|-----------------------------------------------|-----------------------------------------------|---------------|
|               | field              | Chin | Mazurkewicz | Lastiasih | Meyerhoff Bazara | Luciano Decourt | Plaxis |
| BP 98         | 1200               | 2000 | 1550        | 1650,79   | 2177,09          | 985,3           | 1620   |
| BP 145        | 700                | 1111 | 1080        | 846,17    | 2104,05          | 903,6           | 1029,5 |
| BP 190 (F)    | 700                | 769  | 800         | 709,98    | 1233,49          | 889,6           | 1381,2 |
| BP 334        | 800                | 1429 | 1050        | 1650,79   | 1998,52          | 1444,3          | 1185,8 |
| BP 355 (F)    | 265,625            | 417  | 360         | 263,90    | 1234,85          | 843,8           | 540    |

Based on the table 5, it can be seen that the results of the pile test that failure are closer to the results of the interpretation method using the method developed by Lastiasih [3]. Whereas both empirical methods used in this study, the results are closer to the reality in the field is using the method of calculation of the bearing capacity of Luciano Decourt [12]. But when compared with finite elements, the results of finite elements are closer than empirical methods. Chin's interpretation method yields an estimate of the ultimate carrying capacity that is relatively greater compared to other methods. These results are almost the same as the results of research conducted by Zein[2]. The Chin [4] and
Mazurkiewicz [5] method is more graphic so that the results obtained may differ between planners from one another. Therefore in the case of choosing the right approach, it is better to use a specific formula so that whoever does it will get the same results. While for the empirical method Luciano Decourt [12] method was chosen because the carrying capacity produced was more pessimistic than the Bazara - Meyerhoff [13][14] method.

5. Conclusion
Based on research conducted, it can be concluded as follows
1. Analysis by interpreting the ultimate bearing capacity based on the results of the field test pile has been carried out in this study. The temporally results that obtained in this study namely data interpretation in the form of a relationship curve between load and settlement is most appropriate using the quadratic hyperbolic method by Lastiasih. As for the empirical formula, it is recommended to use the Luciano Decourt method.
2. Based on the results of interpretations that are still varied it is necessary to do a lot of data so that correction factors can be obtained for the methods of Luciano Decourt and Meyerhoff Bazara, so the results of empirical calculations are close to the results of field testing
3. To get the ultimate bearing capacity that is right in the field by using finite elements, axysymmetry modeling is carried out and the piles are assumed linearly elastic soils rather than plates. And smoothing the mesh around the pile and Mohr Coulomb modeling undrained conditions for the soil layer.

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