Determining the weight of the hammer based on expert experience for estimating load-carrying capacity

M K Wardani¹, M F N Aulady¹, W Frido¹, and S Hendri¹

¹Institut Teknologi Adhi Tama Surabaya, East Java, Indonesia

milakusuma@itats.ac.id

Abstract. Inexperience geotechnical engineer has difficulty in specifying the best type of weight of the hammer. Here, this study aims to help inexperience geotechnical engineers to decide the optimum weight of the hammer on the pile driving machine. The Bayes method is applied to decide between drop hammer and diesel hammer pile driving machines. Furthermore, we interviewed the expert by several questions about the criteria of the best pile driving machine using a Likert scale. The result suggests that the best type of pile driving is Drop Hammer. The weight of the hammer required to carry out the piling process is 0.9 ton. Recommendations for allowable bearing use the Meyerhof 1976 method. This condition meets the workload that more 141.14 tons at a depth of 26 m when using a square pile dimension of 35 x 35 and 40 x 40 cm. The dimensions are 45 x 45 cm, the recommended depth of piles is 26 m. the allowable bearing carrying when compared with the dynamic capacity using the Hilley, ENR, and WIKA methods meet the requirement. This is given the result of the allowable load-carrying capacity of 170 tons that less than 280 tons until 390 tons at dynamic capacity.

1. Introduction
Foundation is one of the crucial parts of building work. The foundation work is tied to the soil condition at the construction location. A construction location with a deep hard soil layer is potentially needed attention by planning engineers. The planning engineers might use a pile foundation for foundation work in this situation [1]. Hence, to start pile foundation work in construction work, we must pay attention to several factors that affect to pile foundation. The factor such as installation method, selection of pile driver, and loading conditions are some of the essential parts that possibly affect the project successfully and efficiently [2].

The project successfully and efficiently is also determining by many factors. One of them is the experience of the engineer levels. For planning, engineers with less experience determining the pile driver might solve the complex problem because it will affect the time and cost of the project. Piles that are driven into place are generally considered to be low displacement or high displacement, depending on the amount of soil that must be pushed out of the way as the pile is driven [3]. Thus, the selection of a pile driver should be considered at the same time when planning the project.

This paper aims to help less experience planning engineers chose the optimum pile driver based on expert experience using the Bayes method. Bayes method is one of the methods that can help to make decisions based on complex criteria [4]. In 2016, Waluyo et al. [5] study about using the Bayes method for selecting long of pile foundation based on the risk analysis. The result indicates that the Bayes method successfully helps the engineer for the complexity of selecting long of the pile. In 2017, Yulianto [6] studied about selecting a pile foundation based on the noise of the pile driver and vibration of the
pile driver. The result is related to the previous study that the Bayes method is could help to solve the foundation problem. However, this study focusses on selecting pile driving. Either, we are continuing to calculate the pile foundation using the pile driver expert judgment. For calculating the pile foundation, we used the static method and dynamic method. In completion, we confirm our calculation result with expert experience.

2. Method
This study starts with a questionnaire about pile driver selection. The questionnaire was given to the expert with various positions related to foundation work. The questionnaire involves the Site Manager, Site Engineer, Quality control engineer, Quality surveyor engineer, and Supervisor engineer in two cities, Surabaya and Gresik, East Java province, Indonesia. The expert was selected with the experience for foundation work for more than five years. Four factors that we determined based on our literature study. The factor is Environmental impact, cost impact, productivity impact, and location accessibility. However, the expert respondent fills the questionnaire using a Likert scale from 1 to 5; the number indicates that the low impact of the pile driver to the factor that was determined into high impact. Afterward, we calculated the total value using the Bayesian formula, as shown in equation 1.

\[
\text{The total value } I = \sum_{j=1}^{m} ij(Criteria[ij])
\]

Where:
- Total Value $I$ = the final total value of the i-th alternative
- $ij$ value = the first alternative value for j criteria
- Criteria $[ij]$ = level of importance quality value for j-criteria
- $i$ = 1, 2, 3, n ; n = number of alternative
- $j$ = 1, 2, 3…m; m = number of criteria

Next, we calculated the pile foundation. We collected data of standard penetration test (SPT) also the specification of the pile driver based on expert judgment. SPT was performed during the advancement of soil boring to obtain a disturbing drive sample (split barrel type) of the soil being penetrated and an approximate measure of its dynamic resistance. NSPT test obtained results relative density ($Dr$ (%)) and the ground shear angle ($\phi$) based on the value of the number of blow (N). If energy efficiency (Ef) is measured, then the energy-corrected SPT N-value adjusted to 60% efficiency (N60). N-values measured in the field should be corrected to N60 for all soils [7]. Theoretically, it is mandatory to measure Ef to get the proper correction to N60. In the absence of data, AASHTO (2004 with 2006 Interims) [8] recommends Ef = 60 for rope and cathead systems, i.e., donut and safety hammers and Ef = 80 for automatic hammer systems. Others, The NSPT value, must be corrected for the groundwater level and the overburden stress.

The prediction of pile load-carrying capacity can be achieved using different methods such as pile load test, dynamic analysis, static analysis based on soil properties from laboratory tests, and static analysis utilizing the results of in situ tests such as cone penetration test or standard penetration test. According to Meyerhof, when a pile is driven into loose sand, its density is increased, and the horizontal extent of the compacted zone has a width of 6-8 times pile diameter [9, 10]. The principle of the load-carrying capacity of the pile foundation, including the Static method (Using the principles of classical soil mechanics), Dynamic and loading test (full-scale load test). The ultimate load-carrying capacity of a pile is given by equation 2 [11]:

\[
Q_u = Q_p + Q_s
\]
where:
Q_p = capacity of the pile point
Q_s = load-carrying frictional resistance (skin friction) derived from the soil–pile interface

Meyerhof N-SPT is a more actual method to use in foundation planning because the carrying capacity value is closest to the static loading test result. Later, we calculated the end bearing pile used the following equation:

\[ Q_u = 40 N_b A_p + 0.2 N A_p \]  \hspace{1cm} (3)

Further, Single pile load-carrying capacity for cohesive soil and laboratory data found can used formula based on [10] :

\[ Q_b = A_b x f_b \] \hspace{1cm} (4)

\[ f_b = c_b N_c + P_b \] \hspace{1cm} (5)

where,
Q_b = point bearing single pile (kN)
f_b = end bearing resistance of single pile (kN/m²)
A_b = End Pile Area (m²)
C_b = Cu value at the end of pile
N_c = load-carrying capacity factor (N_c = 9) [14]
P_b = Po, overbudded pressure

On the other hand, for the static method, we used the Meyerhof formula [9]. This Load-carrying capacity Method observed the effect of piling the foundation in different soil layers [9]. It can be described using this illustration in Figure 1 and Figure 2.

![Figure 1](image1.png)

**Figure 1.** Resistance Pile tip and depth of sand between soft soils on the Thick sand layer.

![Figure 2](image2.png)

**Figure 2.** Resistance Pile tip and depth of sand between soft soils thin sand layer.

End bearing resistance with Single pile ultimate load-carrying capacity pays attention to the depth factor. The point bearing pile capacity of a pile is given by equation 6 and 7:
\[ Q_b = Ab \left( 38N \right) * \frac{L_b}{d} \leq 380 N \left( Ab \right) \]  

\[ f_b = 0.40N60' \left( \frac{L}{d} \right) \sigma_r \leq 4N60'\sigma \left( \frac{kN}{m^2} \right) \]  

where,

\( fb = \) end bearing single pile (kN/m²)

\( N_{60} = \) The corrected N-SPT affects field procedures only and overburden pressure

\( \sigma_r = \) stress references = 100 kN/m²

\( L = \) depth (m)

\( D = \) pile diameter (m)

The average N value is calculated using 4D below the pile tip and 4D above the pile tip. \( L_b/D \) is the depth ratio; it can less then \( L/d \) if the soil condition has a variation Layer. Then, \( Ab \) is the area of the end pile. If we have a maximum value from the equation \( L/d \geq 7.5 \), frictional pile capacity used assumed massive pile displacement [12]. The frictional pile capacity of a pile for cohesive soil is given by equation 8:

\[ f_s = \frac{1}{50} \sigma \ N_{60} \left( \frac{kN}{m^2} \right) \]  

where,

\( f_s = \) frictional single pile (kN/m²)

\( N_{60} = \) The corrected N-SPT affects field procedures only

\( \sigma_r = stress \ references = 100 \ kN/m^2 \)

The factor of safety generally used ranges from 2.5 to 4, depending on the uncertainties surrounding the calculation of the ultimate load [13]. The piles were installed by driving (hammering and vibration) and boring techniques. The results of influence of installation methods, show load-carrying capacity increments of 10% in bored piles, 20-22% in hammered driven piles, and 20-30% in vibrated driven piles [14]. Diesel hammer has a more exact shape compared to other hammers. The advantages of Diesel hammer are easy to move, provide big hit carrying capacity, good tool ability, and low fuel cost. The disadvantage is that the work is slow; there are a sound and splash from the lubricating oil, the big hammer tools. The drop hammer system requires a certain height because this system uses a massive hammer. The drop hammer method has the advantages of simple tools; falling height can be checked easily, with little difficulty and low operating costs. In this method, because there is a heavy hammer, it can cause the pile head to be easily damaged, the length of the driving is limited, often becomes a slow eccentricity. The selection of the weight of the pile stacker can be calculated using equation 9:

\[ B = (0.5 \times P) + 600 \ kg \]  

Where \( B \) is the weight of hammer (kg), and \( P \) is the weight of pile (kg). Pile driving equations, such as the Engineering News Formula, were developed that related the pile capacity to the energy of the pile driving hammer and the average net penetration of the pile per blow of the pile hammer [13].

Several equations have been developed to calculate the ultimate capacity of a pile during driving. These dynamic equations are widely used in the field to determine whether a pile has reached a satisfactory bearing value at the predetermined depth. One of the earliest such equations commonly referred to as the Engineering News (EN) Record formula. This method uses derived from the work-energy theory. The pile penetration, \( S \), is usually based on the average value obtained from the last few driving blows. The factor of safety \( FS = 6 \) was recommended for estimating the allowable pile capacity.
\[ Q_u = \frac{E \cdot W R_h \cdot W_r + n^2 \cdot W_p}{S + C \cdot W_r + W_p} \]  

(10)

where,

- \( E \) = efficiency of hammer
- \( C \) = 2.54 mm if the units of \( S \) and \( h \) are in mm
- \( W_p \) = weight of the pile
- \( n \) = coefficient of restitution between the ram and the pile cap

3. Result and Discussion

Table 1. Results Analysis based on Hammer Selection for Pile construction using Bayes Method

| Alternative       | Environmental Impact | Implementation Cost | Pile Productivity | Location Topography | The Value Alternative Score |
|-------------------|----------------------|---------------------|-------------------|---------------------|----------------------------|
| Drop Hammer       | 4                    | 4                   | 4                 | 3                   | 3.75                       |
| Diesel Hammer     | 4                    | 3                   | 2                 | 3                   | 3.05                       |

The result of the Bayes method is illustrated in Table 1. The Table shows that on the environmental impact criteria, the two piles have a high score. This is because of both harm erection and the noise pollution caused by the pile driver. In the cost criteria analysis, there is a slight difference where the drop hammer has higher points than the diesel hammer. This condition is influenced by the fuel requirements of the drop hammer a little bit more than the diesel hammer. The advantage of diesel hammers is because diesel hammer easier to move places. It is a better productivity criterion than drop hammers. As for topography and location, the two alternative piling tools are easy to access to the project. Then from that value is continued by giving the Quality weight value. The most significant weight value is given to the environmental impact criteria. The second is given on the productivity criteria and the topography of the location. The quality weight value is given to the implementation cost. Table 2 shows the composition and calculating the decision matrix based on equation 1. From the matrix that has been compiled, it is found that the total weight is 3.75. This value of a drop hammer is selected in the use of the piling process.

Table 2. Calculation of the Decision Matrix Using the Bayes Method

| Alternative       | Score Criteria | Quality Score | Alternative Score |
|-------------------|----------------|---------------|-------------------|
| 1                 | 2              | 3             | 4=2*3             |
| Drop Hammer       | 4              | 0.3           | 1.2               |
|                   | 4              | 0.2           | 0.8               |
|                   | 4              | 0.25          | 1                 |
|                   | 3              | 0.25          | 0.75              |
| Total value       |                | 3.75          |                   |
| Diesel Hammer     | 4              | 0.3           | 1.2               |
|                   | 3              | 0.2           | 0.6               |
|                   | 2              | 0.25          | 0.5               |
|                   | 3              | 0.25          | 0.75              |
| Total value       |                | 3.05          |                   |
From the results of the Bayes method analysis, then calculate the impact weight of the pile tool. In this case, the pile weight used according to the service piling company is 486 kg/m. From these results, the weight of the hammer required for the piling process is calculated and based on the pile driver specification, namely selected with the Kubota V1505 Turbocharged engine type. Then the weight of the hammer required to carry out the piling process is 0.9 ton.

The calculation of the allowable load-carrying capacity for a single pile based on the consultant's recommendation at the first point soil investigation is 28 m deep with a $Q_{allow} = 120$ tons. Whereas at the second point, a soil investigation depth of 24-26 m is recommended. So, we analyse two Static load-carrying capacity.

Table 3. Comparison Allowable load-carrying capacity, Working load and Dynamic Capacity

| Points | Depth (m) | Pile dimension cm | Meyerhof 1956 | Meyerhof 1976 | Working Load ton | Dynamic capacity (ton) |
|--------|-----------|-------------------|---------------|---------------|------------------|------------------------|
| DB1    | 24        | 35 x 35           | 70.45         | 113.80        |                  | 332,45                 |
|        | 26        |                   | 74.25         | 111.09        |                  | 293,6                  |
| DB2    | 24        | 35x35             | 132.72        | 169.34        | 141.14           | 391,1                  |
|        | 26        |                   | 85.56         | 129.03        | 141.14           | 293,6                  |
| DB1    | 24        | 40x40             | 90.45         | 141.18        |                  | 320,67                 |
|        | 26        |                   | 165.12        | 174.20        | 141.14           | 283,2                  |
| DB2    | 26        | 40x40             | 101.76        | 162.53        |                  | 384,4                  |
|        | 24        |                   | 106.29        | 119.18        |                  | 384,4                  |
| DB1    | 26        | 45 x 45           | 108.81        | 175.29        |                  | 377,2                  |
|        | 24        |                   | 201.84        | 179.71        |                  |                        |
| DB2    | 26        | 45 x 45           | 120.12        | 200.50        |                  |                        |

Table 3 shows a comparison between the two static methods at the two points of soil investigation. Besides, the calculation results are also compared to workload and the calculation of dynamic capacity. At two points of investigation, the recommended depth of piles is the same at a depth of 24-26 m. It is known that in the Meyerhof 1956 method, the load-carrying capacity value is smaller than the working load. Except at the DB2 point of 24 m depth with dimensions of 40x40 and 45x45 cm, the value of the load-carrying capacity meets the working load. Whereas in Meyerhof 1976 method, it is obtained that the allowable load-carrying capacity value meets the two points of investigation. The dimensions of 40x40 and 45x45 with a depth of 24 m at point DB1 and point DB2. The allowable load-carrying capacity is almost the same as the load obtained at point DB1 with dimensions 35x35 cm, depth of 26 m, namely 141.18 tons. The coefficient value influences this at the pile tip and the NSPT calculation from the pile tip. When using the Meyerhof 1956 method, the most massive load-carrying capacity value is at the DB2 point with dimensions of 45 x 45 cm and a depth of 24 m. However, at a depth of 26 m, the load-carrying capacity decreased in all pile dimensions—the conditions of the subgrade influence this from clay silt to sand. Overall, the value of the carrying capacity of sand in the Meyerhof method is smaller than the type of clay soil. The calculation method in clay is influenced by the Cu value, while the Nq value influences the sand due to the shear angle of the soil. Overall, comparisons between static methods versus dynamic methods are satisfactory. The allowable load-carrying capacity less or equal with dynamic load-carrying capacity. Thus, the drop hammer selection from the recommended Bayes method can be used for this case.

4. Conclusions
Drop hammer was selected from the results of the Bayes method analysis using a questionnaire on the expert. The quality weight value is 3.75 higher than the diesel hammer. Drop hammer selected, namely Kubota V1505 Turbocharged engine type. Then the weight of the hammer required to carry out the
The static allowable load-carrying capacity, which is close to the working load value, is Meyerhof 1976 method. At the DB2 point, the allowable load-carrying capacity value only differs from 3% - 6% if the pile dimensions increase. At point DB1, the load-carrying capacity is still under the working load. The value of the Meyerhof 1976 static carrying capacity fulfills the requirements in planning because it is smaller than the dynamic carrying capacity. This study, though, needs improvement. In this study, we did not calculate the time and cost to confirm the efficiency. However, it just confirms that we help inexperience engineering with expert decisions. In the future, this study continuing try to make another questionnaire to determine how to select the piling method for another case pile foundation implementation.

5. References

[1] Gunaratne M. The foundation engineering handbook. CRC Press, 2013.
[2] Poulos HG, Davis EH. Pile foundation analysis and design. 1980.
[3] Day RW. Foundation Engineering Handbook: Design and Construction with the 2009 International Building Code. McGraw-Hill, https://books.google.co.jp/books?id=ui9ZswEACAAJ (2010).
[4] Marlina A. Metode Bayes Untuk Menentukan Kelayakan Calon Tenaga Kerja Luar Negeri [Bayes Method To Determine Eligibility of Prospective Overseas Workers]. Moneter: Jurnal Keuangan dan Perbankan; 1.
[5] Waluyo B, Sulistiyono H, Murtiadi S. Metode Bayes Untuk Pemilihan Panjang Tiang Pancang Beton Berdasarkan Analisis Risiko Pada Jembatan Banyumulek Lombok Barat [Bayes Method for Selecting Concrete Pile Length Based on Risk Analysis at Banyumulek Bridge, West Lombok]. Spektrum Sipil 2017; 3: 156–166.
[6] Yulianto J. Pemilihan alat pancang menggunakan expert choice [The choice of stake using expert choice]. Jurnal Riset Rekayasa Sipil 2017; 1: 50–58.
[7] Samtani NC, Nowatzki EA. Soil and Foundations Reference Manual - Volume 1. FHWA-NHI-06-088, Washington DC: National Higway Institute.
[8] American Association of State Highway and Transportation Officials. AASHTO LRFD Bridge Design Specifications, Customary U.S. Units: 2006 Interim Revisions. American Association of State Highway and Transportation Officials, https://books.google.co.jp/books?id=b2omAAAACAAJ (2006).
[9] Mayerhof G. Bearing capacity and settlement of pile foundations. Journal of Geotechnical and Geoenvironmental Engineering; 102.
[10] Meyerhof G. Compaction of sands and bearing capacity of piles. Transactions of the American Society of Civil Engineers 1959; 126: 1292–1322.
[11] Nadella K, Wardani MK, DS AI, et al. Perbandingan Daya Dukung Tiang Pancang dengan Metode Statis dan Dinamis pada Proyek SBE Plant PT. Ecooils Jaya Indonesia. 2019, pp. 545–550.
[12] Hardiyatmo HC. Fondasi II. Edisi Kelima Yogyakarta: Universitas Gajah Mada.
[13] Das BM. Principles of foundation engineering. Cengage learning, 2015.
[14] Adejumo T. Research Article Effects of Shape and Technology of Installation on the Bearing Capacity of Pile Foundations in Layered Soil.