# A Comparative Study of Pile Bearing Capacity Analysis Results Based on the Empirical Method (Standard Penetration Test) and the Finite Element Method

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***ABSTRACT***

This study aims to compare the bearing capacity of steel pile foundations using two approaches: an empirical method based on Standard Penetration Test (SPT) data with Meyerhof's formula, and a numerical method based on the Finite Element Method (FEM). The research object is a steel pipe pile foundation with a diameter of 850 mm and a depth of 43 meters, used in a port dock structure. Data were obtained from field tests, including bore logs and corrected N-SPT values. The Meyerhof method was applied to manually calculate the end-bearing and shaft friction capacity of the pile, while the FEM approach involved two-dimensional geometric modeling using soil parameters derived from field data and technical assumptions. The analysis results indicate that the Meyerhof method yields an allowable bearing capacity of 7855.23 kN/m², whereas the FEM method results in a capacity of 1432.16 kN/m², with a comparison ratio of 0.1823. This discrepancy suggests that the finite element method provides more conservative and realistic results by thoroughly considering soil-structure interaction. Therefore, the finite element method is recommended for foundation design in large-scale projects or cases requiring high accuracy.

**Keywords:** Bearing capacity, finite element method, meyerhoff

## 1. INTRODUCTION

In the planning of infrastructure such as buildings, bridges, roads, and piers, the foundation plays a crucial role in connecting the ground with the load of the superstructure [1]. The foundation is an essential structural element in any construction project. All structures with engineered superstructures bearing on the ground must be supported by a robust and stable foundation [2]. A deep foundation is a type of foundation constructed at a certain depth, with its bearing capacity influenced by surface soil conditions and structural loads. It is used to support the weight of a structure when hard soil is located deep beneath the ground surface. Typically, deep foundations are installed at depths starting from 3 meters below the surface [3]. Pile bearing capacity refers to the ability of a pile to support the loads acting on it. Therefore, the bearing capacity of a pile foundation must be greater than the applied loads to safely support the structure [4]. In addition to estimation methods, pile bearing capacity can also be determined through field testing and theoretical approaches. In geotechnical engineering theory, there are several methods available for analyzing the bearing capacity of deep foundations [5].

There are various methods for calculating pile bearing capacity, each with its own characteristics and suitability depending on the parameters, assumptions, and limitations used [6]. In addition to supporting the vertical loads of a jetty structure, pile foundations also play a crucial role in resisting lateral loads, current loads, wave loads, wind loads, and seismic loads. Given Indonesia's geographic location in an earthquake-prone region, foundation design and testing must consider the existing bearing capacity to ensure structural safety [7].

Based on the above explanation, this study aims to compare the bearing capacity of foundations using the empirical method based on N-SPT data and the finite element method. The finite element method is a software-based approach used to analyze consolidation, deformation, and water flow through two-dimensional modeling [8]. It works by dividing a domain into several elements, and the more elements used, the more accurate the analysis becomes. This method is widely used by geotechnical engineers; however, the results obtained may vary and are not always consistent with one another [6]. In this study, Steel Pipe Piles (SPP) are used as the foundation, supporting the superstructure of a vehicle terminal jetty with a depth of 43 meters. The research is expected to produce accurate results and provide a measurable comparison between the two analysis methods.

## 2. THEORY AND METHODS

### 2.1 Pile Pondation

Pile foundations are categorized as deep foundations. They consist of structural elements made from materials such as timber, concrete, or steel, designed to transfer loads from the superstructure through soft soil layers to deeper, more competent soil or rock layers. This load transfer occurs either through skin friction along the pile shaft or end bearing at the pile tip [9]. In addition to vertical load transfer, pile foundations are also designed to resist lateral forces acting perpendicular to the pile axis through bending resistance. This type of foundation is commonly employed to transfer structural loads to deeper strata with higher bearing capacity. Moreover, pile foundations are capable of resisting uplift forces due to groundwater pressure and can effectively withstand lateral forces and dynamic loads, such as those caused by earthquakes [10].

### 2.2 Pile Bearing Capacity

Pile bearing capacity is the maximum load that a pile can support axially before failure occurs. In general, the bearing capacity calculation can be conducted using three main approaches: empirical methods, analytical methods, and numerical methods [11]. This study compares the empirical method based on Standard Penetration Test (SPT) results with a numerical method using the finite element approach.

### 2.3 Empirical Method Based on SPT

The Standard Penetration Test (SPT) is a field testing method conducted concurrently with drilling to obtain representative soil samples and assess soil resistance [12]. The N-SPT value reflects the soil's hardness or consistency and can be used to estimate the pile bearing capacity through empirical correlations. One of the methods employed is based on Meyerhof (1956) :

End bearing

$$Qp = (40 \times Nb) \times Ap \qquad (1)$$

Friction bearing

$$Qs = (0{,}2 \times Ns) \times As \qquad (2)$$

Bearing Capacity

$$Qu = Qp + Qs \qquad (3)$$

Dimana,

Qu = Bearing Capacity (ton)
Qp = End bearing (ton)
Qs = Friction bearing (ton)
Nb = N-SPT value at pile tip elevation
Ns = Average N-SPT value
40 = End Bearing resistance coefficient factor
Ap = Pile base area ($m^2$)
As = Pile shaft area ($m^2$)

## 2.4 Finite Element Method

The Finite Element Method is a numerical technique used to solve engineering and mathematical physics problems. This method transforms the analyzed problem into a system of simultaneous equations. The solution provides an approximate result for the unknown values at specific points within a continuous system [13]. In the context of pile bearing capacity, the Finite Element Method (FEM) is capable of modeling the complex interaction between the pile and the surrounding soil, including non-linearity effects, soil plasticity, and lateral deformation. In FEM modeling, the soil is represented as a continuous medium with specific geotechnical properties, while the pile element is modeled using structural elements (e.g., embedded pile or plate element) [14].

## 2.5 Methods

The method applied in this study begins with collecting soil data and structural data. The soil data obtained includes drilling logs, soil classification, and SPT N-values. The next step involves calculating the foundation bearing capacity according to specifications using the Meyerhof method based on the SPT N-values, which yields the pile tip bearing capacity and shaft friction capacity. The subsequent method employs the finite element approach, starting with inputting soil data and the load applied on a single pile to determine the axial force acting on the pile. Below are the drilling log results from the study site with the SPT test show in table 1:

**Table 1. Soil Testing Result Using the Standart Penetration Test**

| Depth (m) | Soil Classification | N-SPT |
|---|---|---|
| 7,45 – 11,45 | Clay | 6 |
| 11,45 – 16,45 | Clay | 12 |
| 16,45 – 19,45 | Silty Sand | 32 |
| 19,45 – 28,45 | Clay | 14 |
| 28,45 – 29,95 | Silty Sand | 23 |
| 29,95 – 37,45 | Clay | 24 |
| 37,45 – 43 | Silt | 28 |
| 43 – 44,45 | Clay | 23 |
| 44,45 – 46,15 | Clay | 28 |
| 46,15 – 46,65 | Clay | 20 |

## 3. RESULTS AND DISCUSSION

### 3.1 Results of Empirical Methods (*standart penetration test*)

Calculating the bearing capacity of the foundation based on N-SPT (Standard Penetration Test) data using the Meyerhof method (1956).The results provide the end bearing capacity and shaft (friction) resistance of the pile, allowing the determination of the pile's ability to withstand the allowable pressure based on the soil conditions. The formula from Meyerhof's method (1956) is as follows [15] :

End bearing

$$Qp = (40 \text{ x } Nb) \text{ x } Ap........................(1)$$

Friction bearing

$$Qs = (0{,}2 \text{ x } Ns) \text{ x } As........................(2)$$

Bearing Capacity

$$Qu = Qp + Qs........................(3)$$

The N-value (blow count) from the SPT (Standard Penetration Test) data at each depth is corrected according to field procedures (energy correction) and overburden pressure correction. The corrected N-SPT values are presented in table 2 :

**Table 2. Corrected N-SPT Value**

| No | Depth (m) | Soil Classification | N-SPT | Corrected N-SPT |
|---|---|---|---|---|
| 1 | 7,45 – 11,45 | Clay | 6 | 7,13 |
| 2 | 11,45 – 16,45 | Clay | 12 | 15 |
| 3 | 16,45 – 19,45 | Silty Sand | 32 | 23,64 |
| 4 | 19,45 – 28,45 | Clay | 14 | 17,50 |
| 5 | 28,45 – 29,95 | Silty Sand | 23 | 17,09 |

| | | | | |
|---|---|---|---|---|
| 6 | 29,95 – 37,45 | Clay | 24 | 30,50 |
| 7 | 37,45 – 43 | Silt | 28 | 16,85 |
| 8 | 43 – 44,45 | Clay | 23 | 28,75 |
| 9 | 44,45 – 46,15 | Clay | 28 | 35 |
| 10 | 46,15 – 46,65 | Clay | 20 | 25 |

Pile bearing capacity with Meyerhoff (1956) methods

Pile base area

Ap $= \frac{1}{4}\ x\ \pi\ x\ d^2$

$= 0,567\ m^2$

End Bearing capacity (Qp)

Qp = (40 x $N$b) x Ap

= (40 x 16,85) x 0,567

= 382,25 ton

Pile shaft area

As = 2 x $\pi$ x r x L

= 2 x 3,14 x 0,4 x 43

$= 108,02\ m^2$

Ns = 18,24

Friction Bearing (Qs)

Qs = (0,2 x $N$s) x As

= (0,2 x 18,24) x 108,02

= 418,74 ton

Ultimate Bearing Capacity

Qu = Qp + Qs

= 462,20 + 374,41

= 836,61 ton

Allowable Bearing Capacity

Qall $= \frac{Qu}{SF}$

$= \frac{836,61}{2,5}$

= 320,40 ton

**Table 3. The bearing capacity results at each elevation using the Meyerhof (1956) method**

| No | Depth (m) | Soil | Corrected N-SPT (Np) | Ns | Qp | Qs | Qu | Qall |
|---|---|---|---|---|---|---|---|---|
| 1 | 7,45 – 11,45 | Clay | 7,13 | 7,13 | 161,64 | 163,54 | 325,18 | 130,07 |
| 2 | 11,45 – 16,45 | Clay | 15 | 11,06 | 340,30 | 253,92 | 594,22 | 237,69 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 | 16,45 – 19,45 | Silty Sand | 23,64 | 15,26 | 536,40 | 350,18 | 886,59 | 354,64 |
| 4 | 19,45 – 28,45 | Clay | 17,50 | 15,82 | 397,01 | 363,06 | 760,07 | 304,03 |
| 5 | 28,45 – 29,95 | Silty Sand | 17,09 | 16,07 | 387,66 | 368,89 | 756,55 | 302,62 |
| 6 | 29,95 – 37,45 | Clay | 30,50 | 18,48 | 691,94 | 424,09 | 1.116,03 | 446,41 |
| **7** | **37,45 – 43** | **Silt** | **16,85** | **18,24** | **382,25** | **418,75** | **801,01** | **320,40** |
| 8 | 43 – 44,45 | Clay | 28,75 | 19,56 | 652,24 | 448,9 | 1.101,14 | 440,45 |
| 9 | 44,45 – 46,15 | Clay | 35 | 21,27 | 794,03 | 488,28 | 1.282,31 | 512,93 |
| 10 | 46,15 – 46,65 | Clay | 25 | 21,65 | 567,16 | 496,84 | 1.064,00 | 425,60 |

Based on the results shown in Table 3, a pile foundation with a diameter of 850 mm and a depth of 43 meters has an ultimate bearing capacity of 801.01 tons, with an end-bearing capacity of 462.20 tons, a shaft resistance of 374.41 tons, and an allowable bearing capacity of 320.40 tons using a safety factor of 2.5.

### 3.2 Finite Element Method (FEM)

### 3.3 Soil Parameters

The parameters used are based on the corrected N-SPT values and assumptions derived from soil classification, referring to the book *Foundation Analysis and Design* by Joseph Bowles (1997).The parameters assumption derived from soil classification as follows in table 4:

**Table 4. Parameters for the Finite Element Method (FEM)**

| No | N-SPT | Soil Classification | γ sat (kN/m$^3$) | C' (kN/m$^2$) | φ | υ | E' (kN/m$^2$) |
|---|---|---|---|---|---|---|---|
| 1 | 6 | Clay | 18,02 | 5 | 25 | 0,4 | 3000 |
| 2 | 12 | Clay | 19,39 | 10 | 32 | 0,4 | 7000 |
| 3 | 32 | Silty Sand | 19,26 | 0,05 | 32 | 0,3 | 12000 |
| 4 | 14 | Clay | 19,82 | 22 | 31 | 0,4 | 10000 |
| 5 | 23 | Silty Sand | 19,13 | 0,05 | 31 | 0,3 | 12000 |
| 6 | 24 | Clay | 22,06 | 40 | 32 | 0,4 | 15000 |
| 7 | 28 | Silt | 19,20 | 0,05 | 32 | 0,3 | 12000 |
| 8 | 23 | Clay | 19,22 | 30 | 32 | 0,4 | 15000 |
| 9 | 28 | Clay | 20,25 | 40 | 32 | 0,4 | 15000 |
| 10 | 20 | Clay | 20,03 | 40 | 32 | 0,4 | 15000 |

### 3.4 Input of soil Parameters into the software

The analysis results of a single pile foundation using the finite element method were obtained through an axisymmetric model by inputting parameters based on field test data and assumptions derived from actual site conditions and soil classification. The geometric model was designed to reflect the actual condition of the steel pile embedded in the soil, using an embedded beam element with a diameter of 0.8 m and a thickness of 24 mm, with a spacing of 10 times the pile diameter. The geometric modeling is illustrated as follows in figure 1:

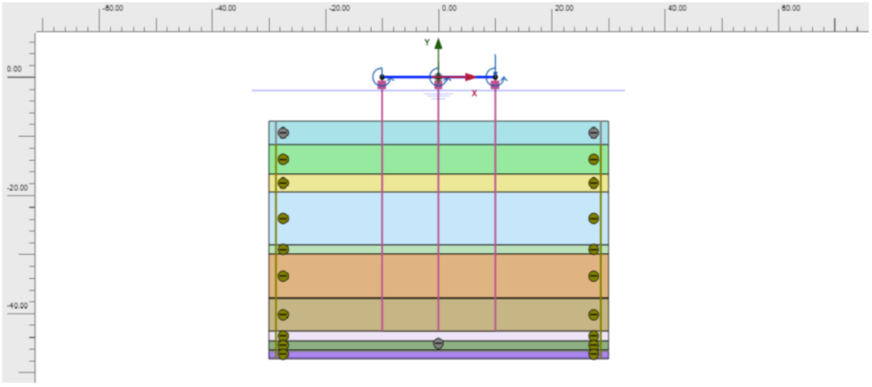

**Figure 1. Geometry Modeling in the Finite Element Method**

After inputting the soil data according to Table 4, the finite element program generates the mesh output as shown in figure 2:

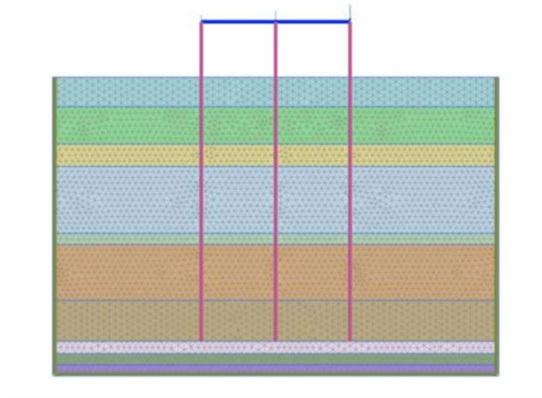

**Figure 2. Finite Element Program Mesh Output**

### 3.5 Load Application Using XYZ Software

Before modeling the dock structure using XYZ software, both the superstructure and substructure were modeled to determine the axial forces, bending moments, and shear forces acting on each pile. The analysis results from the XYZ software indicate that the maximum axial force is observed at the rear pile location as follows in table 5 :

**Table 5. Load input Finite Element Method**

| Internal Forces | Value | Unit |
|---|---|---|
| P | 3074,483 | kN |
| F2 | 8,599 | kN |
| F3 | 3,307 | kN |

| | | |
|---|---|---|
| M2 | 321,2911 | kN-M |
| M3 | 8,9704 | kN-M |

### 3.6 Output using Finite Element Method

**Settlement**

Following the finite element analysis, the settlement at the foundation base was determined to be 0.03882 m. The correlation between the ultimate bearing capacity (Qu, kN/m²) and the settlement (Uy) is illustrated in figure 3 :

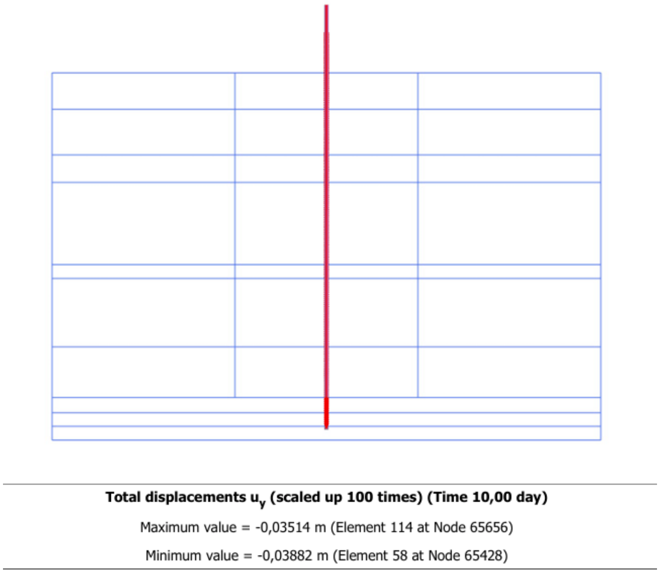


**Figure 3. Settlement of Pile Foundations Using the Finite Element Method**

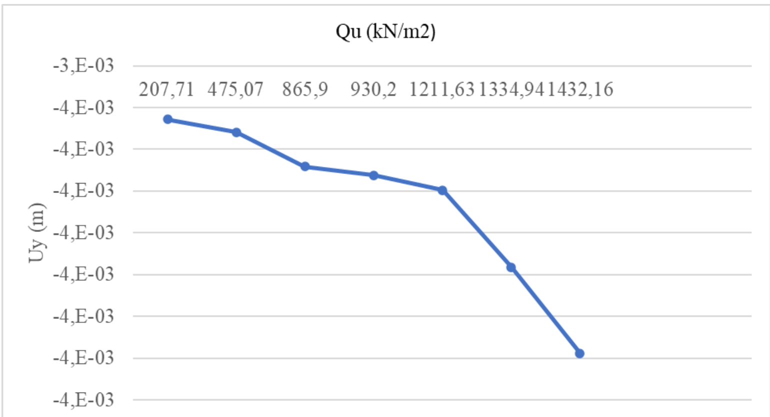


**Figure 4. Curve of axial force versus settlement along the Y-Axis**

### 3.7 Comparison

The comparison results between the empirical method using Meyerhof's formula (1956) and the finite element method are as follows in table 6 :

**Table 6. The comparison result**

| Program carrying capacity ($kN/m^2$) | Empirical carrying capacity ($kN/m^2$) | Ratio |
|---|---|---|
| 1432,16 | 7855,23 | 0,1823 |

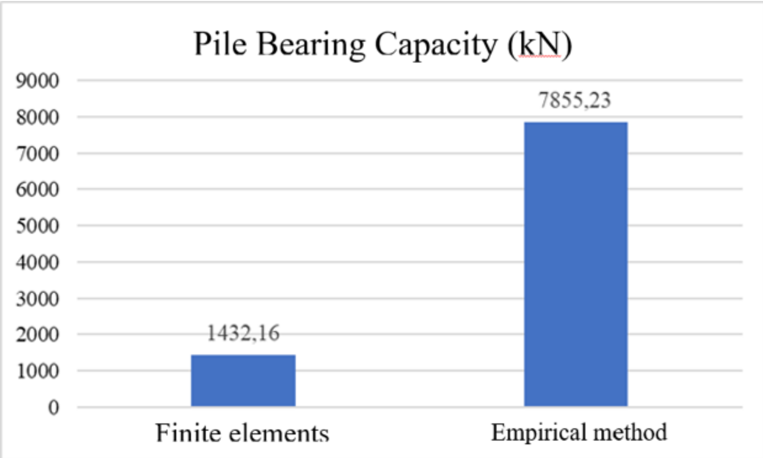


**Figure 5. Comparison Graph of Empirical and Finite Element Methods**

## 4. CONCLUSIONS

Based on the results of the analysis, it can be concluded that there is a significant difference between the pile bearing capacity calculated using the empirical method (SPT) and the finite element method. The empirical method offers a simpler and faster approach, but both methods heavily depend on the quality of the field soil test data and tend to be more conservative. On the other hand, the finite element method provides more detailed and realistic results as it takes into account the interaction between the soil and the structure through comprehensive two-dimensional numerical modeling. The comparison results show that the ultimate bearing capacity value obtained from the finite element method is lower than that from the Meyerhof method, with a result ratio of approximately 0.1823. This indicates that the numerical approach yields a more conservative and safer estimate for foundation design. Therefore, for large-scale projects or critical structures that require high precision, the finite element method is more recommended. However, the choice of method should still be adjusted according to project requirements, site conditions, and data availability. In addition, it is essential to verify calculation results with field test data to ensure the reliability and safety of the foundation design.

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