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Analysis of Pile Foundation Bearing Capacity and Soil Classification in Padang City

Liliwarti, Silvianengsih, Tiara Mahardika, Bagaskoro M, Farizi Abddilah

Civil Department, Politeknik Negeri Padang, Limau Manis, Padang, 25164, Indonesia

Corresponding author: liliwarti@pnp.ac.id

Abstract— Padang City, west of Sumatra, is highly vulnerable to natural disasters such as earthquakes, landslides, and floods. The soil conditions in this area, consisting of tuff, silica, and rocks with low cohesion, pose challenges due to their weak bearing capacity, increasing the risk of ground movement or subsidence. This study analyzes the bearing capacity of pile foundations and soil classification in the Sungai Sapih area using the Cone Penetration Test (CPT) method and soil classification based on the Bagemann method. Investigations were conducted at five sounding points (S1–S5) in Sungai Sapih to understand the soil characteristics and provide optimal foundation planning recommendations. The results of this study indicate that the soil layers are dominated by clay, with variations such as organic clay, very stiff clay, and clay loam, all of which tend to have low end-bearing capacity. At depths of up to 11 meters, the cone resistance (qc) values were very low at all points, indicating that the pile foundation cannot rely on end-bearing support at this depth. However, increased friction along the pile shaft significantly contributes to the ultimate bearing capacity of the pile foundation. Hard soil layers were identified at depths of 12–16 meters, with qc values of approximately 150 kg/cm², providing a reference for deep foundation design. Based on the result of this study, the use of piles foundation and bored piles is recommended to reach the hard soil layers to ensure structural stability. Additionally, an analysis of soil settlement is necessary due to the high potential for deformation in the clay layers. This study is expected to serve as a guideline for safe and sustainable foundation planning in the Sungai Sapih area, rapidly developing as a center for government and public facilities in Padang City.

Keywords— Bearing capacity; Pile foundation; Soil classification

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I. INTRODUCTION

Padang City is an area that is prone to various natural disasters, such as earthquakes, landslides and floods. [1],[2],[3] Geographically, Padang City is located on the west coast of Sumatra Island. According to Adrin Tohari, Padang City composed of 4 (four) rock layers, consisting of sedimentary rock, volcanic rock and sedimentary rock [4], the type of soil in this area contains tufa, silica and bolder with relatively low cohesion, so it is easily separated when exposed to water. This type of soil does not have a good bearing capacity, so there is a risk of causing ground movement or subsidence if it is not calculated properly. Soil carrying capacity and soil type play an important role in development planning and regional development in the city of Padang. Soil bearing capacity can be determined based on investigations (soil investigations) based on laboratory data and field data. The most common field investigations carried out on building construction projects, roads, bridges and other public facilities are the Cone Penetration Test (CPT) which is also called the sondir test.

This paper discusses the bearing capacity of pile foundations based on the Cone Penetration Test (CPT) and soil classification using the Bagemann method, conducted in the Sungai Sapih area, Padang City. Given the rapid development in this area, with numerous government centers and public facilities being constructed, a study on soil conditions and bearing capacity is necessary as a foundation for proper planning. This information is essential to provide guidance for the community and local government in supporting safe and sustainable development

In civil building construction planning, the bearing capacity of the soil has a very important role. The bearing capacity of the soil is the ability of the soil to withstand the foundation load without collapsing due to shear which is also determined by the shear strength of the soil. Soil has the property of increasing its density and shear strength when subjected to pressure. If the load acting on the foundation soil has exceeded its limit bearing capacity, the shear stress generated in the foundation soil exceeds the shear strength of the soil, which will result in shear failure of the soil [5],[6].

Ultimate bearing capacity (Qult) is the maximum pressure that can be accepted by the soil to withstand a load without causing landslides or a failure under and around the foundation [7]

The bearing capacity of shallow deep foundations and the bearing capacity of deep foundations are carried out based on static methods using the Terzaghi method (1943). to calculate the end bearing capacity (Qp) and friction bearing capacity (Qs). Carrying capacity analysis can be carried out based on field test results from Standard Penetration Test (SPT) [8] and Cone Penetration Test (CPT) testing [9]

The CPT test, also known as the static cone penetration test, is widely used in Indonesia. This test is a test used to calculate the bearing capacity of the soil. The values of static cone resistance or cone resistance (qc) and adhesive resistance (fs) are obtained from tests and can be directly correlated with the soil bearing capacity [10]. The value of (qc) and (fs) can also indicate the identification of the type of soil and its consistency. In sandy soil, the qc value is greater than in fine-grained soil. In dense and very dense sand, light sondir generally cannot penetrate this layer [11], [12]. The comparison of the amount of resistance fs and qc, known as the friction ratio (Rf), can be used to determine soil classification [13]. Several research results show that coarse-grained soils have a small Rf value (<2%), while for fine-grained soils (silt and clay) the Rf value is higher [14], [13]

II. Materials And Method

1. Soil Classification based on CPT

   Bagemann developed soil classification based on CPT data in 1965. There is a correlation between sleeve friction and cone resistance [15].

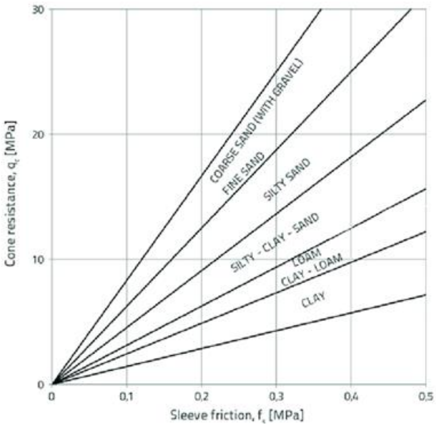

Fig 1. Bagemann Method of Soil Classification

2. Soil bearing capacity based on CPT Test for Pile Foundations

   The bearing capacity of piles can be obtained from CPT or cone penetration test (CPT) data. The mobilized end resistance of the pile must be equivalent to the end resistance during the penetration test. Hardiyatmo (2001) suggests that for closed-end piles, the unit end resistance of the pile is equal to the cone resistance (qc). However, for open-end piles or bored piles, the unit end resistance is taken as 70% of the cone resistance [16]. The ultimate net bearing capacity (Qu) is calculated using the general equation:

   with,

$$Q_u = Q_b + Q_s = A_b.\, q_c + A_s.f_s \text{ ....(1)}$$

   Ab: area of the pile base, As : surface area of the pile shaft, qc: unit end resistance of the pile, fs : unit skin friction resistance of the pile, Wp: weight of the pile.

   The soil-bearing capacity based on the CPT test, developed by Bagemann, states that the load-bearing capacity of the pile foundation is a combination of end resistance and friction [8],[14]

$$Q_u = Q_b + Q_s \text{ ....(2)}$$

$$Q_b = \omega.A_b.q_c \text{ ....(3)}$$

$$Q_s = \Sigma\ (A_s.\, q_f) \text{..(4)}$$

Qu: ultimate bearing capacity, Qb: end bearing capacity, Qs: friction bearing capacity, ω: reduction factor for nominal end resistance, Ab: cross-sectional area of the pile base (m^2), qc: average cone resistance value calculated from 8D above the pile base to 4D below the pile base, As: surface area of the pile shaft, qf: average value of the shaft resistance (kN/m^2)

a. Pile Capacity in Granular Soil

   Based on the recommendations of Vesic (1967), the unit end resistance of the pile (fs) can be considered equal to the cone resistance (qf), thus expressed as fb = qc. The ultimate end resistance of the pile (Qb) is calculated using the formula:

   Qb = Ab.qc..(5)

   where the average value of qc is taken from a depth of eight times the pile diameter (8d) above the base of the pile to four times the pile diameter (4d) below the base of the pile. Vesic also states that the unit skin friction resistance (fs) for concrete pile walls is twice the skin friction resistance of the cone tip (qf), resulting in fs = 2 qf (kg/cm^2). Meanwhile, for H-profile steel piles, the value of fs is equal to the value of qf (kg/cm^2).

   Empirically, the unit skin friction resistance between the pile wall and the soil can be obtained from the cone tip resistance values as proposed by Mayerhof (1956), indicating that this method can be applied to concrete and timber piles in sandy soil, as well as to H-profile steel piles in sandy soil. This approach is crucial in the design and analysis of pile bearing capacity to ensure the safety and efficiency of structures.

b. Cohesive In-Soil Pile Capacity
In cohesive soil conditions, static cone resistance (qc) is related to undrained cohesion (cu) through the formula :

$$Cu.Nc = qc\ (kg/cm^2) \quad (6)$$

where the value of Nc varies between 10 and 30, depending on the sensitivity, compressibility, and adhesion between the soil and the probe. In calculations, the value of Nc is generally taken between 15 and 18 (Bagemann, 1965).

The pile tip resistance at the average qc value is calculated from a depth of eight times the pile diameter (8d) above the base of the pile to four times the pile diameter (4d) below the base of the pile. The friction resistance per unit area (fs) for piles can be considered the same as the friction resistance of sondir blankets (qf), so it is expressed as fs = qs (kg/cm²).

The ultimate capacity of a pile can be expressed by the equation :

$$Qu = Ab\ qc\ \ As\ qf\ (kg) \quad (7)$$

where Ab is the area of the bottom end of the pile (cm²), As is the area of the pile wall (cm²), qc is the static cone penetration resistance (kg/cm²), and qf is the static cone friction resistance (kg/cm²). This approach is important to ensure accurate evaluation of the bearing capacity of piles in cohesive soils.

III. Result and Discussion

This study evaluates soil-bearing capacity in Padang City using the Cone Penetrometer Test (CPT). It focuses on Sungai Sapih Area sites to analyze soil engineering properties for construction suitability. The research area will be strategically selected based on its geological diversity and relevance to construction. Data collection involves using a standard cone penetrometer to measure soil resistance in the Sungai Sapih Area, with multiple tests at each site to ensure reliability.

Soil bearing capacity will be calculated using the relationships for undrained cohesion and ultimate bearing capacity. Statistical analysis will summarize the data and identify relationships between soil parameters.

Results from CPT and soil analysis will offer insights into soil load-bearing capacity, validated against existing literature and standards. The findings will be compiled into a comprehensive report, discussing methodologies, detailed results, and implications for civil engineering practices in Padang City. This research aims to provide critical information for safe and effective construction practices.

The CPT data was obtained from secondary sources related to building construction in the Sungai Sapih area, Aia Pacah, Kota Padang, covering five test points. Bearing capacity analysis was conducted using the Bagemann method, with soil classification also based on the same approach. Table 1 presents the results of the CPT tests at the five locations in Sungai Sapih, Kota Padang. The data provides an overview of the soil conditions at the site, including soil layer depth and parameters such as cone resistance (qc) and friction resistance (qs), which are essential for determining the foundation's bearing capacity. Based on the analysis results, each test point indicates variations in soil consistency and type, serving as the foundation for planning and selecting the optimal foundation type for construction in the area.

TABLE I. MAXIMUM END RESISTANCE VALUE (QC)

No	Location	Dept (m)	Cone Resiatance (q_c) (kg/cm²)
1	S1	12,6	150
2	S2	13,4	150
3	S3	13	150
4	S4	15,6	150
5	S5	14,8	150

As shown in Table 1, the depth of the hard soil layer at the five test points ranges from 12.6 meters to 15.6 meters. Hard soil is generally defined as soil with a high cone resistance value, specifically qc ≥ 150 kg/cm². At all test points (S1 to S5), this qc value has been reached, indicating that a load-bearing layer exists at these depths capable of supporting the structural load.

The pile foundation depth is planned with variations of 3 m, 6 m, 9 m, and 12.6 m. The piles used are circular concrete piles with a diameter of 40 cm. The analysis of pile foundation bearing capacity is carried out using the Bagemann method. This calculation is based on CPT test results with the Bagemann method, where the reduction factor for the nominal end resistance value (ω) is 0.50.

The ultimate bearing capacity equation for pile foundation is expressed as:

$$Q_u = Q_b + Q_s$$

With,
Qu : Ultimit bearing capacity, Q_b : $\omega.A_b.q_c$,
Q_s : $\Sigma\ (A_s.\ q_f)$

a. Bearing Capacity of Pile Foundations Calculation (S1)
Foundation Depth: 3 meters.
Ultimit Bearing Capacity Calculation

1. End Bearing Capacity (Q_b)
   - Cross-Sectional Area of Pile Tip (A_b): 0.126 m²
   - Avarage of qc (8D-4D): 210,292 kN/m²
   - Formula Qb =ω.Ab.qc
     Qb = 0,5* 0,1256 m² * 210,292 kN/m² = 13,206 kN
2. Friction Capacity (Qs)
   - Surface Area of the Pile (As): 3,768 m²
   - Average (qs): 3,267 kN/m²
   - Formula Qs = Qs = Σ (As. qf)

     Qs= Σ(3,768 m²*3,267 kN/m² = 12,309 kN
3. Ultimate Bearing Capacity (Qu):
   - $Q_u = Q_b + Q_s$
   - Qu=13,206 kN + 12,309 kN = 25,515 kN

b. Soil classification by Bagemann Method

The soil classification of the CPT test results is obtained from the Bagemann graph (figure 2), which shows a correlation between sleeve friction and cone resistance.

Subsequently, the analysis results of the bearing capacity at each CPT/location test, as well as the soil classification from S1 to S5, are presented in Figures 3 to 12.

1. Bearing Capacity and soil classification at location/point S1

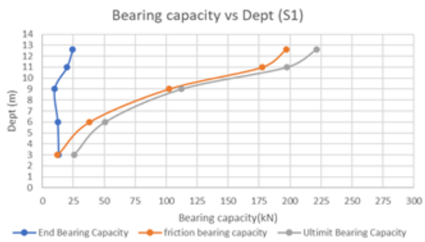

Fig 2. Foundation bearing capacity at point S1

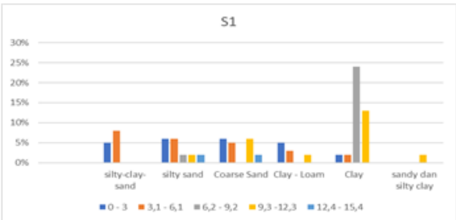

Fig 3. Soil classification at point S1

2. Bearing Capacity and soil classification at location/point S2

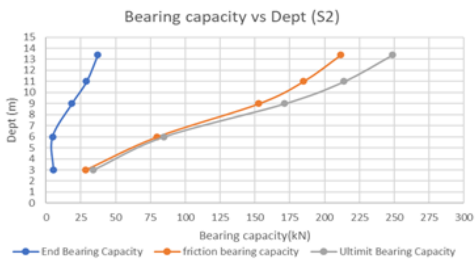

Fig 4. Foundation bearing capacity at point S2

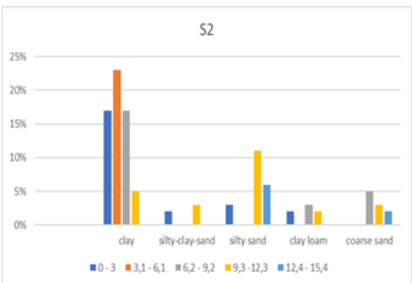

Fig 5. Soil classification at point S2

3. Bearing Capacity and soil classification at location/point S3

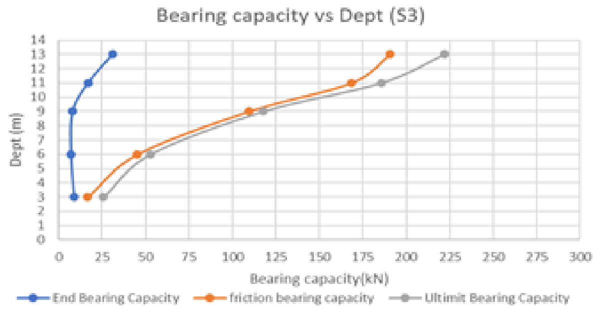

Fig 6. Foundation bearing capacity at point S3

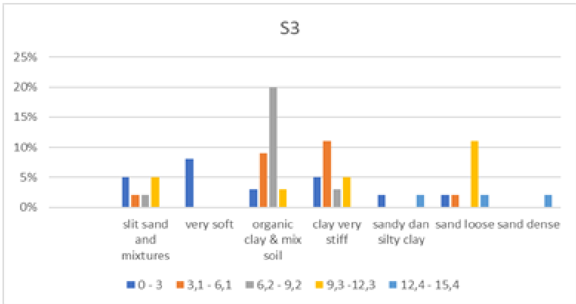

Fig 7. Soil classification at point S3

4. Bearing Capacity and soil classification at location/point S4

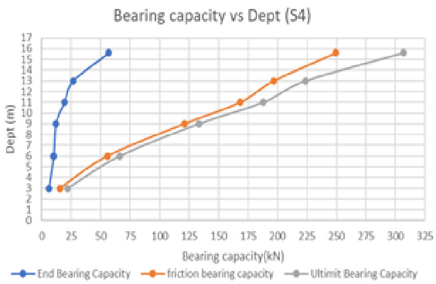

Fig 8. Foundation bearing capacity at point S4

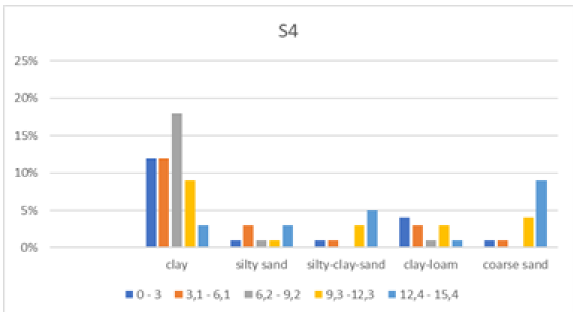

Figure 9. Soil classification at point S4

5. Bearing Capacity and soil classification at location/point S5.

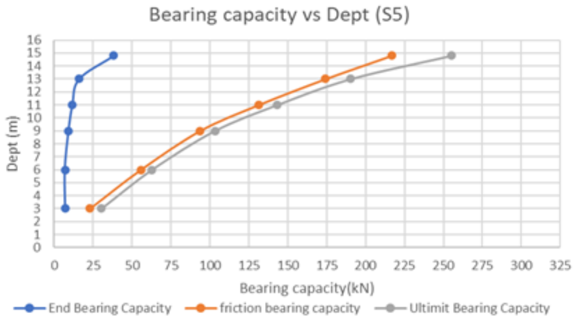

Fig 10. Foundation bearing capacity at point S5

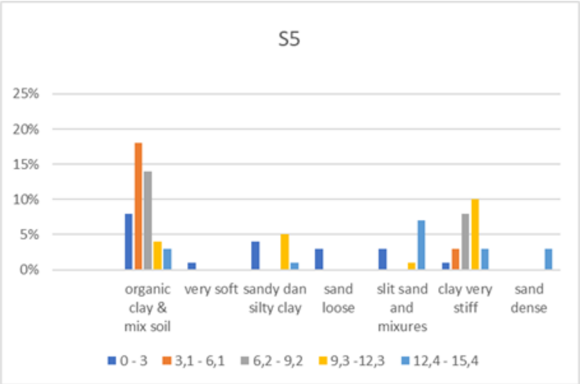

Figure 11. Soil classification at point S5

a. Analysis at location/ Point S1

- Soil Bearing Capacity (Figure 3)

  At depths of 0–9 meters, the end-bearing capacity of the pile is relatively low. However, the increasing frictional resistance with depth indicates that the foundation relies more on friction along the pile surface to support the load.

- Soil Classification (Figure 4)

  At depths of 0–9.2 meters, the soil layer is predominantly composed of clay. Clay soils tend to have low end-bearing capacity and significant cohesive properties. This aligns with the observed characteristics, which show low cone tip resistance.

b. Analysis at location/ Point S2)

- Soil Bearing Capacity (Figure 5)

  At point S2, from a depth of 0 to 8.6 meters, the cone tip resistance is low, resulting in low end-bearing capacity. However, it starts to increase at depths between 8.8 and 13.4 meters. This condition indicates the soil's limitations in supporting large loads at those depths.

- Soil Classification (Figure 6)

  At depths of 0 to 15.4 meters, approximately 62% of the soil composition is clay. This zone has a low potential for supporting pile foundations and is prone to settlement if high loads are applied.

c. Analysis at location/ Point S3

- Soil Bearing Capacity (Figure 7)

  Very soft soil is found from a depth of 0 to 11 meters. The low cone tip resistance indicates inadequate bearing capacity, making the use of pile foundations with loads at the tip ineffective.

- Soil Classification (Figure 8)

  The soil composition at this point is also dominated by organic clay and very stiff clay, reinforcing the assumption that the soil is not optimal for supporting large loads. This soil layer carries a high risk of deformation, especially when saturated with water or subjected to heavy loads.

d. Analysis at location/ Point S4

- Soil Bearing Capacity (Figure 9)

  At point S4, the end-bearing capacity is low down to a depth of 11 meters. However, friction along the surface of the pile contributes significantly to the total bearing capacity of the foundation. This indicates that at this location, the use of pile foundations will rely more on friction than on end support.

- Soil Classification at point S4 (Figure 10)

  At this location, the soil is predominantly clay, making up 54% of the composition, which results in relatively low bearing capacity.

e. Analysis at location/ Point S5

- Soil Bearing Capacity at point S5 (Figure 11)

  At point S5, the soil is predominantly clay from a depth of 0 to 13 meters, exhibiting relatively low end-bearing capacity. The clay layer at this depth indicates a low potential for end-bearing capacity and a reliance on frictional support.

- Soil Classification (Figure 12)

  The soil at this location is dominated by clay and clay loam, which are types of soil with low bearing capacity.

At the Sungai Sapih area, hard soil is found at depths between 12 to 15 meters across all five CPT points. This indicates that the soil in this location has low bearing capacity, making it unsuitable for supporting large loads unless the foundation is placed down to the hard soil layer. All CPT points show a similar pattern, with clay layers dominating at various depths, exhibiting low end-bearing capacity but significant frictional support [17], [18]

IV. CONCLUSION

Based on the soil classification results using the Bagemann method from five testing points (S1–S5) in the Sungai Sapih area, Aia Pacah, and Padang City, most of the soil layers are dominated by clay with various compositions and consistencies, such as organic clay, very stiff clay, and clay loam. Clay soils have low bearing capacity and are cohesive, making them inadequate for supporting large loads without special handling.

According to the analysis of pile foundation-bearing capacity for the Sungai Sapih area, foundation planning should prioritize the use of long piles that reach the hard soil layer while considering the contribution of friction to ensure optimal foundation performance. The hard soil layer is located at depths of 12.6 to 15.6 meters, with a cone tip resistance (qc) value of 150 kg/cm². The soil conditions at the testing location are relatively uniform, which will facilitate a more straightforward and predictive foundation planning process.

Deep foundations such as driven piles or bored piles are recommended to ensure that the foundation reaches the hard soil layer and has adequate bearing capacity. Settlement control is necessary due to the susceptibility of clay layers to settlement, requiring close monitoring of changes in soil conditions, particularly in the event of humidity changes.

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