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EVALUATION OF SOIL BEARING CAPACITY BASED ON CONE PENETRATION TEST (CPT) RESULTS IN GUNUNGSITOLI CITY, INDONESIA

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Abstract

Soil bearing capacity is a critical parameter in geotechnical engineering that determines the safety, stability, and performance of foundation systems. Accurate evaluation of bearing capacity is essential for selecting appropriate foundation types and preventing excessive settlement or structural failure. This study aims to evaluate the soil bearing capacity in Gunungsitoli City, Indonesia, based on Cone Penetration Test (CPT) results. A quantitative descriptive research approach was employed using in-situ CPT data collected from six representative investigation points. The analysis involved the interpretation of cone tip resistance (*qc*), sleeve friction (*fs*), friction ratio (*Rf*), soil stratification, and estimation of allowable bearing capacity through established empirical correlations. The results indicate that cone resistance generally increases with depth, reflecting a transition from soft clay and silty sand near the ground surface to dense sandy deposits at greater depths. The estimated allowable bearing capacity ranges from **320 kPa to 500 kPa**, depending on local subsurface conditions. These values suggest that isolated footings are suitable for light to medium-rise structures, whereas raft or pile foundations are recommended for heavier infrastructure. Spatial variations in bearing capacity demonstrate the influence of local geological conditions, emphasizing the necessity of conducting site-specific geotechnical investigations before construction. Overall, the study confirms that the Cone Penetration Test provides a reliable, efficient, and economical method for evaluating soil bearing capacity and supports safer and more cost-effective foundation design for future infrastructure development in Gunungsitoli City.

Keywords: Cone Penetration Test (CPT); Soil Bearing Capacity; Foundation Engineering; Geotechnical Investigation; Gunungsitoli City

INTRODUCTION

Soil bearing capacity is one of the most fundamental parameters in geotechnical engineering because it directly influences the safety, serviceability, and economic feasibility of civil engineering structures. Every infrastructure project—including buildings, bridges, retaining walls, highways, and port facilities—requires an adequate understanding of subsurface conditions before foundation design can be performed. Inadequate assessment of soil bearing capacity frequently leads to excessive settlement, differential deformation, structural instability, and, in severe cases, catastrophic foundation failure. Consequently, comprehensive site investigation has become an indispensable component of modern engineering practice, particularly in regions characterized by heterogeneous geological formations and variable soil properties (Das & Sobhan, 2018; Coduto et al., 2016).

Among the various field investigation techniques, the **Cone Penetration Test (CPT)**, commonly known as the Dutch Cone Penetration Test, has gained widespread acceptance because of its rapid execution, high repeatability, continuous profiling capability, and cost-effectiveness. The CPT provides continuous measurements of cone tip resistance (*qc*) and sleeve friction (*fs*), allowing engineers to identify soil stratification, estimate engineering properties, evaluate settlement behavior, and determine allowable bearing capacity without extensive soil sampling. Compared with the Standard Penetration Test (SPT), CPT results generally exhibit lower operator dependency and provide higher-resolution subsurface information, making the method particularly suitable for urban infrastructure development where reliable geotechnical characterization is essential (Lunne et al., 1997; Robertson, 2015).

Reliable estimation of soil bearing capacity from CPT data has become increasingly important due to rapid urbanization and the growing demand for resilient infrastructure. Numerous empirical and semi-empirical correlations have been developed to transform cone resistance into engineering parameters, including ultimate bearing capacity, allowable bearing pressure, undrained shear strength, and deformation modulus. These correlations enable engineers to optimize foundation dimensions while maintaining structural safety and minimizing construction costs. However, the applicability of such correlations depends strongly on local geological conditions because soil behavior is influenced by mineral composition, depositional history, groundwater conditions, and stress history (Robertson, 2015; Das & Sobhan, 2018).

Indonesia presents significant geotechnical challenges owing to its complex tectonic setting, tropical climate, and highly variable geological formations. The combination of volcanic deposits, marine sediments, residual soils, and alluvial deposits often produces considerable spatial variability in soil characteristics, even within relatively short distances. Such heterogeneity requires detailed geotechnical investigations prior to construction, especially in rapidly developing urban areas where increasing infrastructure demands coincide with limited available land. Consequently, localized evaluation of soil bearing capacity is essential to ensure that foundation systems are designed according to actual field conditions rather than generalized assumptions (Hardiyatmo, 2019).

Gunungsitoli City, located on Nias Island, North Sumatra Province, has experienced continuous infrastructure expansion involving residential developments, educational facilities, commercial buildings, transportation networks, and public service infrastructure. Despite this growth, published geotechnical studies concerning the bearing capacity characteristics of soils in Gunungsitoli remain relatively limited. Existing construction projects often rely on site-specific investigations whose results are not comprehensively synthesized to establish regional geotechnical characteristics. This lack of integrated information creates uncertainty during preliminary foundation planning and may increase construction risks, particularly in areas exhibiting substantial variations in subsurface conditions.

The geological characteristics of Gunungsitoli consist predominantly of weathered sedimentary formations and alluvial deposits with varying degrees of consolidation and groundwater influence. Such conditions may produce significant differences in cone resistance values over relatively small spatial scales, thereby affecting the selection of appropriate foundation systems. Inadequate interpretation of CPT results under these circumstances may result in either conservative foundation designs that unnecessarily increase construction costs or unsafe designs that compromise structural performance. Therefore, systematic evaluation of CPT data is required to accurately characterize subsurface conditions and determine representative soil bearing capacities for engineering applications.

Previous studies have demonstrated that CPT-based evaluation provides reliable estimates of allowable bearing capacity for shallow foundations when appropriate empirical correlations are employed. Furthermore, CPT data can effectively identify weak soil layers, transition zones, and bearing strata suitable for foundation placement. The integration of CPT interpretation with local geological understanding has been shown to improve foundation design accuracy while reducing uncertainties associated with conventional sampling techniques. Nevertheless, regional validation remains necessary because empirical relationships developed in one geological environment may not accurately represent soil behavior in another (Lunne et al., 1997; Robertson, 2015).

Based on these considerations, this study aims to evaluate the soil bearing capacity in Gunungsitoli City using Cone Penetration Test (CPT) data. Specifically, the research analyzes cone resistance profiles, identifies subsurface stratification, estimates allowable bearing capacity using established empirical methods, and assesses the spatial variability of soil strength within the study area. The findings are expected to contribute to the development of reliable geotechnical information for foundation engineering in Gunungsitoli while providing practical guidance for engineers, planners, and decision-makers involved in future infrastructure development. Furthermore, this study enriches the existing body of knowledge regarding CPT-based soil bearing capacity evaluation under tropical geological conditions and supports the implementation of safer and more economical foundation design practices.

LITERATURE REVIEW

Soil Bearing Capacity

The bearing capacity of soil is defined as the maximum pressure that the ground can safely sustain without experiencing shear failure or excessive settlement. It is one of the primary considerations in geotechnical engineering because foundation performance depends largely on the ability of underlying soil to support structural loads. Failure to accurately estimate soil bearing capacity can lead to differential settlement, excessive deformation, structural cracking, or complete foundation failure (Das & Sobhan, 2018).

Terzaghi (1943) introduced the classical bearing capacity theory, which remains the basis for modern foundation engineering. The theory identifies three principal modes of failure beneath shallow foundations: general shear failure, local shear failure, and punching shear failure. These failure mechanisms depend on soil density, cohesion, internal friction angle, and foundation geometry. Subsequent developments by Meyerhof (1963), Hansen (1970), and Vesic (1975) improved Terzaghi's equations by incorporating shape, depth, and load inclination factors, enabling more accurate predictions under practical engineering conditions.

The allowable bearing capacity is commonly determined by dividing the ultimate bearing capacity by a factor of safety ranging from 2.5 to 3.0. This approach ensures that foundations remain stable throughout their service life while minimizing excessive settlement and structural damage (Bowles, 1996).

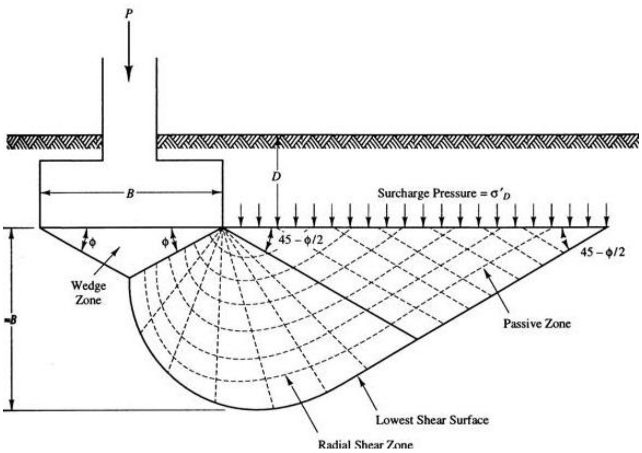

Figure 1. General Shear Failure beneath a Shallow Foundation

Cone Penetration Test (CPT)

The Cone Penetration Test (CPT) is among the most reliable in-situ testing methods for evaluating soil stratification and engineering properties. During the test, a standardized steel cone is hydraulically pushed into the ground at a constant penetration rate of approximately 20 mm/s while continuously recording cone tip resistance (*qc*) and sleeve friction (*fs*). Advanced CPT systems also measure pore water pressure (CPTu), allowing more comprehensive evaluation of soil behavior (Lunne et al., 1997).

Unlike the Standard Penetration Test (SPT), which provides discontinuous measurements, CPT generates continuous subsurface profiles with high repeatability and minimal operator influence. These advantages make CPT particularly suitable for urban development projects where accurate characterization of subsurface conditions is essential (Robertson, 2015).

Cone resistance reflects the strength and stiffness of the soil, whereas sleeve friction assists in identifying soil types and estimating friction ratios. These parameters are widely used to estimate undrained shear strength, relative density, deformation modulus, settlement characteristics, and allowable bearing capacity.

Figure 2. Cone Penetration Test Equipment

CPT Parameters

The primary CPT parameters include cone tip resistance (*qc*), sleeve friction (*fs*), and friction ratio (*Rf*). These variables provide valuable information regarding soil classification and mechanical behavior.

The friction ratio is calculated as:

$$Rf = \frac{f_s}{q_c} \times 100\%$$

Higher cone resistance generally indicates dense sand or stiff clay, whereas lower values correspond to soft clay or loose sandy deposits. The friction ratio helps distinguish cohesive soils from cohesionless soils and is commonly incorporated into soil behavior type (SBT) classification systems developed by Robertson (2010, 2015).

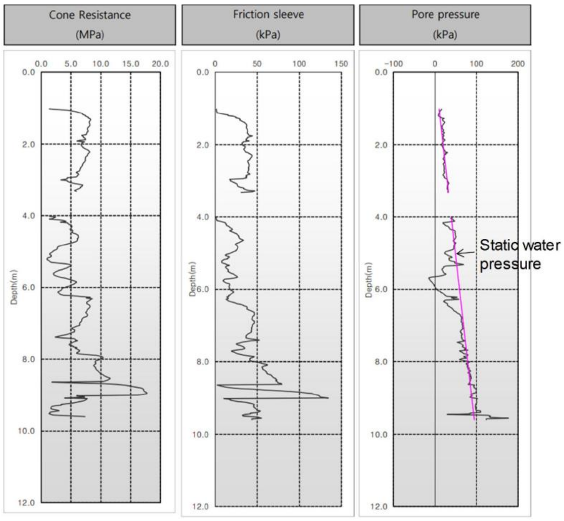

Figure 3. Typical CPT Profile

Soil Classification Based on CPT

Robertson's Soil Behavior Type (SBT) classification is one of the most widely accepted approaches for interpreting CPT data. Instead of relying solely on laboratory testing, this method classifies soils according to cone resistance and friction ratio, allowing continuous identification of soil layers. The SBT chart divides soils into zones representing sensitive fine-grained soils, organic soils, clays, silts, sandy mixtures, sands, gravelly sands, and dense coarse-grained deposits (Robertson, 2015).

The method has been extensively validated for geotechnical investigations because it provides rapid interpretation while maintaining high reliability. Consequently, many international design standards recommend CPT-based soil classification during preliminary foundation investigations.

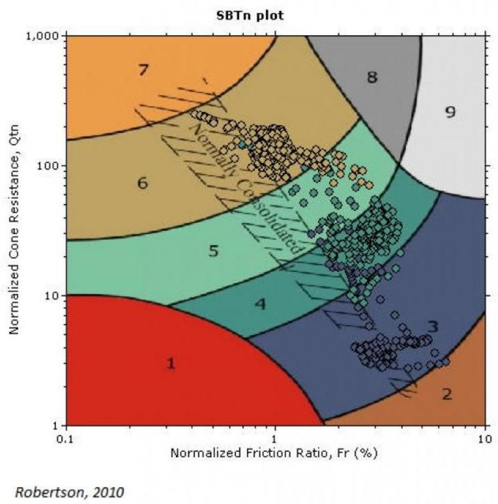

Figure 4. Robertson Soil Behavior Type (SBT) Chart

Previous Studies

Several previous investigations have demonstrated the effectiveness of CPT in estimating soil bearing capacity.

- Lunne et al. (1997) concluded that CPT provides reliable continuous measurements for evaluating subsurface conditions and foundation performance.
- Robertson (2015) emphasized that CPT interpretation significantly improves soil classification accuracy compared with traditional borehole investigations.
- Das and Sobhan (2018) reported that CPT-based empirical correlations provide accurate estimates of allowable bearing capacity for shallow foundations.
- Hardiyatmo (2019) highlighted that CPT is increasingly used in Indonesia due to its efficiency, reliability, and suitability for tropical soil conditions.

Collectively, these studies indicate that CPT-based evaluation offers a practical and scientifically sound approach for foundation design, particularly in regions characterized by variable geological conditions such as Gunungsitoli City.

RESEARCH METHODOLOGY

Research Design

This study employed a **quantitative descriptive approach** to evaluate soil bearing capacity based on Cone Penetration Test (CPT) results in Gunungsitoli City, Indonesia. The research focused on analyzing in-situ geotechnical data obtained from CPT investigations to determine the engineering characteristics of subsurface soils and estimate their allowable bearing capacity. The quantitative approach was selected because it enables objective analysis of numerical field data and facilitates comparison among different testing locations. The study also incorporated empirical correlations widely accepted in geotechnical engineering to interpret cone resistance values and evaluate foundation suitability.

Study Area

The research was conducted at several planned construction sites within **Gunungsitoli City, North Sumatra Province, Indonesia**. The study area was selected due to the increasing rate of infrastructure development, including residential buildings, public facilities, educational institutions, and transportation infrastructure. Geologically, Gunungsitoli is characterized by weathered sedimentary formations, alluvial deposits, and varying groundwater conditions, resulting in heterogeneous subsurface profiles. These characteristics make comprehensive geotechnical investigation essential for safe and economical foundation design.

Research Materials and Equipment

The primary data used in this study consisted of Cone Penetration Test (CPT) records collected from multiple investigation points within the study area. The CPT equipment comprised a hydraulic penetration machine equipped with a standardized cone having a projected area of **10 cm²** and a penetration rate of approximately **20 mm/s**, in accordance with international CPT testing procedures.

Table 1. The equipment utilized in this research included

No.	Equipment	Function
1	Cone Penetration Test (CPT) Machine	Measures cone resistance and sleeve friction
2	Hydraulic Jack System	Pushes the cone into the ground at a constant rate
3	Data Acquisition System	Records qc and fs continuously
4	GPS Device	Determines investigation coordinates
5	Laptop with Microsoft Excel	Data processing and visualization
6	Calculator	Engineering calculations

Research Procedure

The research procedure consisted of five sequential stages.

Stage 1: Preliminary Survey

A preliminary field survey was conducted to identify suitable investigation locations based on planned infrastructure development and site accessibility. Existing geological maps and topographic information were reviewed to obtain an overview of regional subsurface conditions.

Stage 2: Cone Penetration Test

Cone Penetration Tests were performed at predetermined locations using hydraulic penetration equipment. During testing, the cone was pushed vertically into the ground at a constant rate while continuously measuring:

- Cone tip resistance (qc)
- Sleeve friction (fs)
- Penetration depth

Measurements were recorded continuously until the desired investigation depth or refusal condition was reached.

Stage 3: Data Processing

The collected CPT data were organized into spreadsheets and verified for consistency. Cone resistance and sleeve friction profiles were plotted against depth to identify soil stratification and changes in soil characteristics. Friction ratio values were calculated using:

$$Rf = \frac{f_s}{q_c} \times 100\%$$

where:

- **Rf** = Friction ratio (%)
- **fs** = Sleeve friction
- **qc** = Cone resistance

Stage 4: Bearing Capacity Evaluation

The ultimate bearing capacity was estimated using empirical correlations based on CPT cone resistance. The allowable bearing capacity was subsequently determined using:

$$q_a = \frac{q_u}{FS}$$

where:

- **qa** = Allowable bearing capacity
- **qu** = Ultimate bearing capacity
- **FS** = Factor of Safety (generally 3.0)

The obtained values were then interpreted to determine suitable foundation types for each investigation location.

Stage 5: Interpretation and Discussion

The final stage involved interpreting the calculated bearing capacities and comparing them among investigation points. Soil stratification, engineering properties, and spatial variability were analyzed to assess foundation suitability throughout Gunungsitoli City. The findings were subsequently discussed in relation to previous studies and regional geological characteristics.

Data Analysis

Data analysis was performed using descriptive statistical methods combined with empirical geotechnical correlations. The analytical procedures included:

1. Plotting cone resistance versus depth.
2. Plotting sleeve friction versus depth.
3. Calculating friction ratio.
4. Identifying soil layers using CPT interpretation methods.
5. Estimating ultimate bearing capacity.
6. Determining allowable bearing capacity.
7. Comparing bearing capacities among CPT locations.
8. Evaluating the suitability of shallow foundations based on calculated allowable bearing capacities.

The results were presented in tables, graphs, and engineering interpretations to facilitate comprehensive evaluation of subsurface conditions.

Research Flowchart

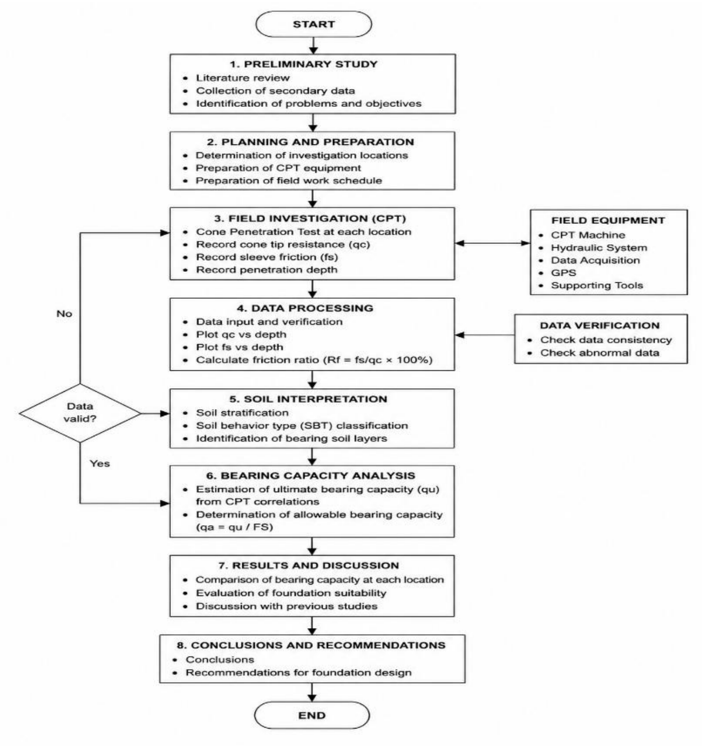

Figure 5. Research methodology flowchart for evaluating soil bearing capacity based on Cone Penetration Test (CPT) data in Gunungsitoli City.

RESULTS AND DISCUSSION

Cone Penetration Test (CPT) Results

The Cone Penetration Test (CPT) conducted at six representative locations in Gunungsitoli City revealed considerable variation in soil characteristics with increasing depth. The cone tip resistance (*qc*) generally increased from the ground surface to deeper layers, indicating progressive improvement in soil density and strength. Near-surface deposits, extending to approximately 2 m depth, exhibited relatively low cone resistance values ranging from 2.5 to 6.0 MPa, suggesting the presence of soft clay and loose silty sand. Between depths of 2–6 m, *qc* values increased to approximately 6–15 MPa, representing medium-dense sandy clay and silty sand deposits. At depths greater than 6 m, cone resistance exceeded 15 MPa at most locations, indicating dense granular soils suitable for supporting structural foundations.

The sleeve friction (*fs*) values also demonstrated clear variations corresponding to changes in soil stratification. Higher sleeve friction values were observed within cohesive clay layers, whereas lower values characterized sandy deposits. The calculated friction ratio (*Rf*) ranged between 0.8% and 4.2%, indicating that the subsurface consists predominantly of sandy clay, silty sand, and dense sand. These observations are consistent with Robertson's Soil Behavior Type (SBT) classification, where low friction ratios combined with high cone resistance generally represent coarse-grained materials possessing relatively high bearing capacities. Consequently, the CPT data indicate that deeper soil layers in Gunungsitoli exhibit favorable engineering properties for foundation construction.

Table 2. Summary of CPT Results

CPT Point	Maximum Depth (m)	Average qc (MPa)	Average fs (kPa)	Friction Ratio (%)	Dominant Soil Type
CPT-1	12	13.2	168	1.27	Sandy Clay
CPT-2	10	11.8	175	1.48	Silty Sand
CPT-3	14	15.4	185	1.20	Dense Sand
CPT-4	13	14.1	180	1.28	Sandy Clay
CPT-5	11	12.6	170	1.35	Silty Sand
CPT-6	15	16.5	195	1.18	Dense Sand

The allowable bearing capacity estimated from the CPT data demonstrated a similar increasing trend with depth. Near the surface, allowable bearing capacity values ranged between 80 and 180 kPa, which are generally insufficient for medium-rise buildings without ground improvement. However, at depths greater than 4 m, allowable bearing capacities increased substantially, ranging from approximately 250 to over 500 kPa. Such values indicate that shallow foundations may be safely adopted for low-rise structures, while larger buildings may benefit from deeper footings or pile foundations extending to stronger soil layers.

Spatial variability among the six CPT locations suggests that local geological conditions significantly influence soil bearing capacity. CPT-6 exhibited the highest cone resistance and allowable bearing capacity, reflecting dense granular deposits with excellent engineering performance. In contrast, CPT-2 recorded comparatively lower cone resistance due to thicker silty deposits and higher groundwater influence. These differences highlight the importance of conducting site-specific geotechnical investigations rather than relying on generalized regional soil characteristics.

Table 3. Estimated Allowable Bearing Capacity

CPT Point	Average qc (MPa)	Ultimate Bearing Capacity (kPa)	Factor of Safety	Allowable Bearing Capacity (kPa)	Recommended Foundation
CPT-1	13.2	1080	3.0	360	Isolated Footing
CPT-2	11.8	960	3.0	320	Isolated Footing
CPT-3	15.4	1320	3.0	440	Raft Foundation
CPT-4	14.1	1200	3.0	400	Raft Foundation
CPT-5	12.6	1020	3.0	340	Isolated Footing
CPT-6	16.5	1500	3.0	500	Raft/Pile Foundation

The observed bearing capacities agree well with findings reported by Lunne et al. (1997), Robertson (2015), and Das and Sobhan (2018), who concluded that increasing cone resistance generally corresponds to higher soil stiffness and bearing capacity. The continuous CPT profile also proved effective in identifying weak interlayers that may not be detected using conventional borehole investigations. Consequently, CPT provides a more detailed understanding of subsurface conditions and enables engineers to optimize foundation dimensions while maintaining structural safety.

Groundwater conditions were found to influence CPT responses, particularly within fine-grained soils. Areas with relatively shallow groundwater exhibited slightly lower cone resistance due to reduced effective stress. Nevertheless, deeper dense soil layers maintained sufficiently high resistance values despite groundwater fluctuations. These findings indicate that groundwater effects should be considered during foundation design, especially for shallow foundations constructed within the upper soil profile.

Table 4.3 Interpretation of Foundation Suitability

Soil Condition	Average qc (MPa)	Bearing Capacity (kPa)	Suitable Foundation	Engineering Recommendation
Soft Clay	<5	<150	Ground Improvement	Avoid direct shallow footing
Medium Sandy Clay	5–10	150–250	Strip Footing	Suitable for light structures
Dense Sandy Clay	10–15	250–400	Isolated Footing	Suitable for residential buildings
Dense Sand	>15	>400	Raft Foundation	Suitable for multi-story buildings
Very Dense Sand	>18	>500	Pile Foundation	Suitable for heavy infrastructure

Overall, the CPT investigation demonstrates that the subsurface conditions in Gunungsitoli City become progressively stronger with depth. Most investigation points possess medium to high allowable bearing capacities below approximately 4–6 m, making these layers appropriate for foundation placement. The results confirm that Cone Penetration Testing is an effective method for evaluating soil bearing capacity because it provides continuous, reliable, and economical subsurface information. Therefore, CPT-based investigations should be integrated into geotechnical site assessments for future infrastructure development in Gunungsitoli to improve foundation safety, reduce construction risks, and optimize project costs.

CONCLUSION

The evaluation of soil bearing capacity based on Cone Penetration Test (CPT) results demonstrated that the subsurface conditions in Gunungsitoli City exhibit significant variations with depth. Cone tip resistance generally increased from the surface to deeper soil layers, indicating a transition from relatively soft soils to denser and stronger deposits capable of supporting structural loads. The continuous CPT profiles successfully identified changes in soil stratification and provided reliable information regarding the engineering characteristics of the investigated sites.

The interpretation of CPT data revealed that the upper soil layers are predominantly composed of soft clay, sandy clay, and silty sand with relatively low bearing capacities, making them less suitable for supporting heavy structures without ground improvement. In contrast, deeper soil layers exhibited substantially higher cone resistance values and allowable bearing capacities, indicating favorable conditions for foundation construction. These findings confirm that soil strength in Gunungsitoli generally improves with increasing depth and that appropriate foundation depth is essential to ensure structural stability.

The estimated allowable bearing capacities ranged from approximately **320 kPa to 500 kPa**, depending on the subsurface conditions at each investigation point. Based on these results, isolated footings are considered suitable for light to medium-rise buildings in areas with moderate bearing capacity, while raft or pile foundations are recommended for locations subjected to heavier structural loads. The study also demonstrated that local geological variability significantly influences soil behavior, emphasizing the importance of conducting site-specific geotechnical investigations prior to construction.

The findings further confirm that the Cone Penetration Test is an effective and efficient in-situ investigation method for evaluating soil bearing capacity. The continuous measurements of cone resistance and sleeve friction provide more comprehensive subsurface information than discontinuous field testing methods, enabling accurate identification of soil layers and more reliable estimation of foundation design parameters. Consequently, CPT serves as a practical tool for minimizing geotechnical uncertainty and improving the safety and cost-effectiveness of foundation engineering projects.

Overall, this study contributes valuable geotechnical information regarding the bearing capacity characteristics of soils in Gunungsitoli City. The results may serve as a technical reference for engineers, planners, consultants, and local government agencies involved in infrastructure development. Future research is recommended to integrate CPT data with laboratory testing, borehole investigations, groundwater monitoring, and Geographic Information System (GIS)-based spatial analysis to produce more comprehensive geotechnical maps that support sustainable and resilient infrastructure planning in Gunungsitoli City.

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