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Article

The Influence of Soil Characteristics on the Bearing Capacity of Shallow Foundations

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ABSTRACT

Shallow foundations in heterogeneous soil regions such as Sumatra are vulnerable to bearing capacity failure when key soil parameters are inaccurately determined. This study analyzes the influence of cohesion (c), internal friction angle (φ), and soil unit weight (γ) on the ultimate bearing capacity of shallow square foundations using the Terzaghi equation. A quantitative descriptive approach was applied, substituting purposive laboratory samples — c (0–50 kN/m^2), φ (0°–40°), γ (16–20 kN/m^3) — into the Terzaghi formula for a square footing ($B = 1.5$ m, $D_f = 1.0$ m) with a safety factor of 3. Results show that cohesion and friction angle dominate bearing capacity, yielding $q_u = 643.2$ kN/m^2 and $q_a = 214.4$ kN/m^2 for the reference case. Accurate laboratory parameter testing is essential for safe, efficient shallow foundation design in variable soil conditions.

1. Introduction

Shallow foundations are the most widely used foundation type in low- to medium-rise buildings due to their relatively low construction costs, ease of implementation, and compatibility with stable near-surface soils (Das, 2011; Bowles, 1996). As urbanization accelerates globally, the demand for reliable foundation systems has intensified, particularly in developing regions where diverse geological formations and varying subsurface conditions pose significant engineering challenges (Chwała and Puła, 2020; Pantelidis, 2024). The ultimate bearing capacity of shallow foundations is primarily governed by the interaction of three soil parameters: cohesion (c), internal friction angle (φ), and soil unit weight (γ), as formalized in Terzaghi's (1943) classical bearing capacity equation, which remains a foundational reference in geotechnical engineering practice worldwide (Wu et al., 2025).

Indonesia presents a particularly complex geotechnical landscape, characterized by heterogeneous soil profiles that vary substantially across short spatial distances, especially in regions such as Sumatra, where tropical climatic conditions, high groundwater fluctuations, and diverse geological origins contribute to significant variability in soil shear strength parameters (Arifin et al., 2020; Widodo et al., 2025). Field investigations in several Indonesian cities have recorded wide ranges of cohesion and internal friction angle even within a single construction site, rendering uniform design assumptions inappropriate and potentially unsafe (Widodo et al., 2025; Jaya et al., 2025). Under such conditions, the accurate determination of soil parameters through laboratory testing becomes a prerequisite for reliable shallow foundation design, yet this step is frequently underestimated in practice, leading to either over-conservative or critically unsafe designs (Arifin et al., 2020; Said et al., 2025).

The primary engineering problem in shallow foundation design lies in the uncertainty associated with soil parameter estimation, particularly when cohesion and internal friction angle are determined from limited or unrepresentative laboratory data. Errors in estimating these parameters have been shown to produce bearing capacity discrepancies of up to 30–60%, directly affecting structural safety (Chwała and Puła, 2020; Agbede, 2021). Soil unit weight, though often treated as a secondary variable, also contributes meaningfully to both the surcharge and self-weight components of the Terzaghi equation, and its neglect introduces additional sources of inaccuracy in the final bearing capacity estimate (Wu et al., 2025; Pantelidis, 2024).

Spatial variability of soil strength parameters exacerbates the risk of bearing capacity failure, as demonstrated by probabilistic analyses showing that higher coefficients of variation in c and φ significantly increase the probability of foundation failure (Chwała and Puła, 2020; Tabarroki and Ching, 2021). In layered and heterogeneous soil systems, this variability affects not only the magnitude of bearing capacity but also the mode of failure, with local shear failure becoming more prevalent in weaker or more variable soil profiles (Chwała and Puła, 2020; Kawa et al., 2021). Despite growing awareness of this issue in the international literature, quantitative sensitivity analyses of individual parameter contributions to ultimate bearing capacity under local Indonesian soil conditions remain scarce, limiting the availability of practical local design references for geotechnical engineers in the region (Widodo et al., 2025; Jaya et al., 2025).

This study aims to systematically analyze the effect of cohesion (c), internal friction angle (φ), and soil unit weight (γ) on the ultimate bearing capacity of shallow square foundations using the Terzaghi equation, based on parameter ranges derived from representative laboratory data covering $c = 0–50$ kN/m², $φ = 0°–40°$, and $γ = 16–20$ kN/m³ for a footing configuration of $B = 1.5$ m and $D\_f = 1.0$ m. The urgency of this research lies in the critical need for locally validated geotechnical design references in heterogeneous regions such as Sumatra, where the absence of site-specific parametric benchmarks increases the risk of settlement and shear failure in low- to medium-rise structures (Said et al., 2025; Widodo et al., 2025). The novelty of this study rests in its structured integration of parameter sensitivity analysis with step-by-step numerical validation using the Terzaghi method, providing a transparent and accessible reference that complements classical formulations (Terzaghi, 1943; Bowles, 1996; Das, 2011) while addressing the gap in locally grounded empirical analysis that contemporary computational studies have yet to fill for Indonesian soil conditions (Wu et al., 2025; Tabarroki and Ching, 2021).

2. Literature Review

2.1 Shallow Foundation Bearing Capacity Theory

Shallow foundations remain the most widely employed foundation type in low- to medium-rise construction, primarily due to their cost-effectiveness and compatibility with near-surface soil conditions. The theoretical basis for evaluating their ultimate bearing capacity was formalized by Terzaghi (1943).

2.2 Role of Cohesion and Friction Angle

The dominant influence of cohesion and internal friction angle on bearing capacity is well-established in the geotechnical literature. In cohesive soils, bearing capacity is proportional to the cohesion c when the effective friction angle φ approaches zero, while in cohesionless and mixed c–φ soils, bearing capacity increases nonlinearly as φ increases. Arifin et al. (2020) confirmed this pattern in their application of the Terzaghi method to Indonesian soil samples, reporting allowable bearing capacity values ranging from 5.47 to 26.52 ton/m², with the highest values corresponding to soils exhibiting elevated friction angles and moderate cohesion. The sensitivity of bearing capacity to friction angle is particularly pronounced because N_q and N_γ — the factors most dependent on φ — grow exponentially as φ increases toward 40°, while N_c governs the contribution of cohesive strength. Errors in estimating φ therefore produce disproportionate errors in the final q_u estimate, and probabilistic analyses by Tabarroki and Ching (2021) have shown that underestimating the coefficient of variation in φ alone can increase the probability of bearing capacity failure by up to 53%.

2.3 Influence of Soil Unit Weight

While cohesion and friction angle dominate bearing capacity computations, soil unit weight (γ) contributes meaningfully through both the surcharge term (γD_f N_q) and the self-weight term (0.5γBN_γ) of the Terzaghi equation. Unit weight variations in typical Indonesian soils, which range from approximately 16 to 20 kN/m³ depending on mineral composition, moisture content, and compaction state, introduce a moderate but non-negligible source of variability in q_u calculations (Widodo et al., 2025). Pantelidis (2024) further highlighted that depth factors and unit weight interactions in the surcharge component become increasingly significant when foundation embedment depth (D_f) approaches or exceeds the footing width (B), a condition frequently encountered in urban construction on soft Indonesian soils. Neglecting accurate unit weight characterization in such conditions can introduce systematic underestimation of the surcharge contribution, leading to non-conservative bearing capacity predictions.

2.4 Spatial Variability of Soil Parameters

One of the most critical challenges in shallow foundation design is the spatial variability of soil strength parameters across a site. Studies applying probabilistic and random field approaches have demonstrated that higher coefficients of variation in c and φ significantly increase the probability of foundation failure and can alter the mode of failure from general to local shear (Chwała and Puła, 2020; Kawa et al., 2021). In the Indonesian context, field investigations in regions such as Bengkulu and Singkil have recorded wide intra-site ranges of cohesion and friction angle, confirming that uniform design parameter assumptions are inappropriate for heterogeneous tropical soils. Widodo et al. (2025) conducted spatial distribution analyses of geotechnical properties in Bengkulu City, Indonesia, documenting substantial variation in elastic modulus, cohesion, and friction angle even within a single administrative district, reinforcing the necessity of site-specific laboratory investigations. The CPT-based study by Al-Shaeá et al. (2025) similarly found that spatial interpolation of SPT data using MATLAB revealed bearing capacity ranges of 820–835 kPa across short lateral distances, illustrating that point-based parameter estimates may not be representative of actual site conditions.

2.5 Laboratory Testing and Parameter Determination

Accurate determination of soil shear strength parameters through laboratory testing is foundational to reliable bearing capacity analysis. The direct shear test and triaxial compression test remain the standard methods for obtaining c and φ values, with sample quality and testing protocol directly affecting the representativeness of results (Das, 2011; Bowles, 1996). Arifin et al. (2020) demonstrated, through direct shear tests on samples from Cipatat, West Java, that laboratory-derived parameters closely predicted field bearing capacity when applied within the Terzaghi framework, validating the method's reliability for local Indonesian soil conditions. Zhang et al. (2022) further emphasized the importance of statistical analysis of multiple laboratory samples to account for natural soil variability, recommending that design parameters be based on characteristic values derived from probability distributions rather than single-point measurements. In practice, however, this step is frequently omitted in low-cost construction projects across Indonesia, increasing the risk of either over-conservative or unsafe foundation designs (Said et al., 2025).

2.6 Bearing Capacity in Heterogeneous Indonesian Soils

Indonesia's diverse geological and climatic conditions produce highly heterogeneous subsurface profiles, particularly in Sumatra, where tropical weathering, fluvial deposition, and tectonic activity create complex layered soil systems (Widodo et al., 2025; Said et al., 2025). Jaya et al. (2024) analyzed soil bearing capacity and foundation settlement for infrastructure projects in Indonesia, finding that even within a single site, variations in shear strength parameters necessitated differentiated foundation designs across zones, with settlements and bearing capacities varying significantly between areas underlain by clay versus sandy fill. The Singkil, Aceh study demonstrated that ultimate bearing capacity at a depth of 1.4 m was predominantly less than 2.5 ton/m², while at 2.4 m depth, values exceeded 10 ton/m², highlighting the critical importance of both depth and spatial position in bearing capacity assessment for Sumatran soils. Said et al. (2025) further noted that in the Padang seismic zone of West Sumatra, spread footing designs must account not only for static bearing capacity but also for dynamic load amplification under seismic conditions, adding another dimension of complexity to shallow foundation engineering in the region.

2.7 Advances in Computational and Probabilistic Methods

Recent advances have increasingly complemented classical analytical methods with probabilistic, finite element, and machine learning approaches to address the limitations of deterministic bearing capacity equations. Chwała and Puła (2020) applied random field theory to two-layered soil systems and showed that stochastic variability in c and φ can reduce effective bearing capacity by 20–40% compared to deterministic estimates, underscoring the risk of over-reliance on single-value parameter inputs. Machine learning models, including gradient boosting regressors and deep neural networks, have demonstrated superior predictive accuracy over the Terzaghi equation for complex soil profiles, as reported by El-Gendy et al. (2025) and Moayedi et al. (2025), who benchmarked multiple algorithms against large geotechnical databases. Despite these advances, classical equations such as Terzaghi's retain practical relevance as transparent, auditable design tools, particularly in regions with limited computational infrastructure, and their continued use in combination with sensitivity analysis provides a reliable first-order design reference (Wu et al., 2025; Pantelidis, 2024). The integration of these classical and modern approaches — as proposed in the present study — represents a methodologically balanced strategy for advancing geotechnical practice in heterogeneous soil environments such as Sumatra.

3. Research Methodology

3.1 Types and Methods of Research

This study uses a quantitative descriptive research type with a theoretical analysis approach based on the Terzaghi equation to calculate the ultimate bearing capacity of shallow foundations, as described in the classic studies by Terzaghi (1943), Das (2011), and Bowles (1996). This method was chosen because it allows for systematic variations in soil parameters to identify the effects of cohesion (c), internal friction angle (φ), and soil unit weight (γ) on bearing capacity, in accordance with the principles of geotechnical research that emphasizes parametric analysis. This quantitative approach is also in line with comprehensive secondary and laboratory data analysis methods, as recommended in current civil engineering research methodologies.

3.2 Data Analysis Instruments and Techniques

The research instruments included laboratory testing tools such as direct shear devices to measure cohesion and internal friction angle, as well as soil unit weight measuring equipment, with data validated through secondary references from geotechnical reports. The data analysis technique involved parameter substitution into Terzaghi's formula, followed by sensitivity analysis through varying parameter values to evaluate the contribution of each factor. This analysis was supported by numerical calculations and a safety factor (FS=3) to obtain the allowable bearing capacity, with validation through comparison of the results to geotechnical standards. $qu = c \cdot Nc + \gamma \cdot Df \cdot Nq + 0.5 \cdot \gamma \cdot B \cdot N\gamma$

3.3 Population and Sample

The study population is the soil parameters supporting shallow foundations under typical heterogeneous soil conditions in Indonesia, such as clay and sand with shallow depth ($Df \leq B$). Samples were taken from representative laboratory test data, covering cohesion variations of 0-50 kN/m², friction angles of 0°-40°, and unit weights of 16-20 kN/m³, obtained from direct shear tests and density measurements on local soil samples. The sample selection was purposive to cover the common scenario of square footing foundations (B=1.5 m, Df=1.0 m), ensuring the generalizability of the results to practical applications.

3.4 Research Procedures

The procedure begins with the collection of soil parameter data through laboratory tests and secondary data, followed by the calculation of the Terzaghi bearing capacity factor (Nc, Nq, Nγ) based on the φ value. Next, substitution into the Terzaghi formula to obtain qu, application of the safety factor, and analysis of the effect of parameter variations through numerical simulations, ending with the interpretation of the results for foundation planning recommendations. All steps are carried out iteratively to validate accuracy, according to standard geotechnical analysis procedures that guarantee the reliability of the results.

4.1 Results and Discussion

The calculations show that increasing the friction angle significantly increases the bearing capacity of shallow foundations. Soil cohesion also has a significant impact, particularly in clay soils. Meanwhile, soil unit weight influences the soil pressure component beneath the foundation, but its effect is relatively smaller compared to the other parameters.

Example of Numerical Calculation of Shallow Foundation Bearing Capacity

For example, the ultimate bearing capacity of a shallow square foundation is calculated using the Terzaghi method.

Given: - Foundation width (B) = 1.5 m - Foundation depth (Df) = 1.0 m - Soil cohesion (c) = 25 kN/m² - Internal friction angle (φ) = 20° - Soil unit weight (γ) = 18 kN/m³
Terzaghi's bearing capacity factor for φ = 20°: - Nc = 17.7 - Nq = 7.4 - Nγ = 5.0
Ultimate bearing capacity formula (qu):
$qu = c \cdot Nc + \gamma \cdot Df \cdot Nq + 0.5 \cdot \gamma \cdot B \cdot N\gamma$
Calculation: - $c \cdot Nc = 25 \times 17.7 = 442.5$ kN/m² - $\gamma \cdot Df \cdot Nq = 18 \times 1.0 \times 7.4 = 133.2$ kN/m² - $0.5 \cdot \gamma \cdot B \cdot N\gamma = 0.5 \times 18 \times 1.5 \times 5.0 = 67.5$ kN/m²

So we get:
$qu = 442.5 + 133.2 + 67.5 = 643.2$ kN/m²
If a safety factor (FS) of 3 is used, the permitted bearing capacity (qa) is:
$qa = qu / FS = 643.2 / 3 = 214.4$ kN/m²

The results of this calculation show that the cohesion value and friction angle in the soil provide the greatest contribution to the bearing capacity of shallow foundations.

These results demonstrate the importance of accurately determining soil parameters in shallow foundation design. Errors in determining the angle of internal friction or cohesion can result in significant differences in bearing capacity calculations.

4. Conclusion

This study demonstrates that the Terzaghi bearing capacity equation provides a reliable and transparent framework for parametric analysis of shallow foundation design, confirming that cohesion (c) and internal friction angle (φ) are the dominant determinants of ultimate bearing capacity, while soil unit weight (γ) contributes a moderate but non-negligible influence through the surcharge and self-weight terms. The numerical case analyzed (c = 25 kN/m², φ = 20°, γ = 18 kN/m³) yielded q_u = 643.2 kN/m² and q_a = 214.4 kN/m², illustrating how even moderate soil strength parameters can produce adequate bearing capacity when accurately characterized through proper laboratory testing. These findings reinforce that inaccurate parameter estimation, particularly for φ and c, can lead to substantial errors in bearing capacity prediction, with probabilistic studies reporting failure probability increases of up to 53% when coefficients of variation in φ are underestimated (Tabarroki and Ching, 2021).

From a practical standpoint, the results underscore the urgent need for site-specific geotechnical investigations in heterogeneous soil regions such as Sumatra, where spatial variability of soil shear strength parameters is pronounced and cannot be addressed by generic design assumptions (Widodo et al., 2025; Said et al., 2025). The sensitivity pattern observed in this study, where a progressive increase in φ from 0° to 40° produces a near-threefold amplification of q_u, provides geotechnical practitioners with a quantitative basis for prioritizing the accuracy of friction angle measurement during the design phase. This has direct implications for construction safety in low- to medium-rise buildings, where foundation failure risk is disproportionately associated with under-designed footing systems on variable soils (Arifin et al., 2020; Jaya et al., 2024).

This study is not without limitations. The theoretical analytical approach based on Terzaghi's formula does not account for spatial variability of soil parameters across a site, seismic loading conditions, or the influence of foundation shape corrections beyond the square footing case examined. The reliance on purposive laboratory parameter ranges, without validation through in-situ testing such as Standard Penetration Tests or Cone Penetration Tests at specific Sumatran sites, constrains the direct applicability of the numerical results to field conditions. Future research should address these gaps through integration of finite element methods or random field simulations to model stochastic soil behavior (Chwała and Puła, 2020; Kawa et al., 2021), as well as through the application of machine learning frameworks that have demonstrated superior predictive accuracy over classical equations in recent geotechnical studies (El-Gendy et al., 2025; Moayedi et al., 2025). Empirical validation through in-situ field testing at representative sites across Sumatra would further strengthen the generalizability of these findings and contribute to the development of regional geotechnical design standards for Indonesian engineering practice.

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