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Research Article

Reliability Assessment of Bored Pile Foundations using a Probabilistic Approach based on SPT Data

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Abstract

Deep foundations perform an important role in supporting structural loads and transferring them to deeper and stronger soil layers. The soil parameters used in geotechnical design practice are commonly obtained from field tests, such as the Standard Penetration Test (SPT), which exhibit a high degree of uncertainty due to variations in soil conditions, testing procedures, and data interpretation. These uncertainties significantly influence the reliability of deep foundation design. Such study aims to evaluate the reliability of bored pile foundations and determine their safety level based on SPT data from five boreholes at various depths using a probabilistic approach. The Monte Carlo simulation method was employed to model the variability of soil strength, determine the reliability index (β), and estimate the probability of failure (Pf). The analysis results show that although the deterministic safety factor (SF ≥ 1) indicates a safe condition, the probabilistic analysis reveals that the system still has a failure probability of approximately 48% and a reliability level of only about 52%, indicating a marginal state. The reliability index limit (β = 0.05) serves as a minimum threshold separating safe and unsafe conditions. Increasing the pile diameter significantly improves the reliability index and reduces the failure probability, demonstrating a strong correlation between design parameters and reliability performance. Overall, the findings highlight that the deterministic approach alone cannot adequately capture soil parameter uncertainty, and reliability-based design (RBD) provides a more realistic and quantitative framework for assessing foundation safety in geotechnical engineering.

Keywords: *bored pile, monte carlo simulation, reliability index, probability of failure.*

1. INTRODUCTION

Infrastructure development in Indonesia continues to grow in line with the increasing demand for high-rise buildings, bridges, and other public facilities. The highly variable soil conditions in tropical regions such as Indonesia ranging from soft clay and saturated sand to hard layers at certain depths require accurate and reliable foundation design. The bored pile foundation has become one of the primary solutions in construction due to its ability to transfer structural loads to hard soil layers and its high load-bearing capacity with relatively small deformation [1], [2].

The reliability of deep foundation design strongly depends on the accuracy of soil parameter characterization. Soil is a natural material with high variability, both laterally and vertically; therefore, geotechnical parameters such as shear strength, cohesion, and Standard Penetration Test (SPT) values cannot be considered constant. Recent studies by Liu et al. [3] and Sadik et al. [4], have confirmed that the spatial variability of SPT and CPT values can cause significant deviations in the calculated bearing capacity even at locations less than 10 meters apart.

In geotechnical engineering practice in Indonesia, foundation design is predominantly performed using a deterministic approach, in which soil parameters are represented by single representative values typically mean or conservative estimates and a global safety factor is applied to account for uncertainties in material properties, loading conditions, and construction quality. Although this method is simple and widely used, it inherently assumes that the adopted parameters and safety factors can adequately represent all possible variations in soil behavior.

However, this approach fails to explicitly capture the probability of failure (Pf) that arises from the

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natural variability of soil properties, such as strength, stiffness, and density, which vary spatially and are influenced by geological processes. Consequently, the deterministic design may lead either to overly conservative foundations, increasing construction costs unnecessarily, or to unsafe designs, particularly when soil variability is high or poorly characterized.

Several studies [5], [6], [7], and [8] have demonstrated that the deterministic method often provides a false sense of safety, as it does not directly relate the statistical variation of soil parameters to the reliability level of the foundation system. In contrast, probabilistic approaches such as Reliability-Based Design (RBD) allow engineers to quantify the likelihood of failure by incorporating parameter uncertainty and load variability, thereby providing a more rational and risk-consistent framework for evaluating geotechnical safety and performance.

The uncertainty of soil parameters in geotechnical engineering design can be quantitatively evaluated through probabilistic analysis, which provides a more rigorous and realistic framework for assessing the safety and performance of foundation systems. Unlike deterministic approaches that rely solely on a single representative value, the probabilistic method incorporates both the mean value and the statistical variability of soil parameters, expressed through their standard deviation, coefficient of variation, and probability distribution function (e.g., normal, lognormal, or beta distribution). By accounting for these statistical characteristics, probabilistic analysis enables engineers to quantify the likelihood of failure (Pf) and determine the reliability index (β), which represents the margin of safety in statistical terms [9], [10]. These two parameters Pf and β serve as the fundamental indicators of system performance under uncertainty, providing a direct measure of how variations in soil strength, stiffness, and load conditions influence the probability of failure.

According to Wang & Dong [1] and Suman et al. [6], the integration of Monte Carlo simulation and Subset Simulation (SS) methods offers a more comprehensive and accurate representation of the probabilistic behavior of geotechnical systems compared to the classical First Order Second Moment (FOSM) approach. This is particularly important in heterogeneous soil conditions, where nonlinear interactions, spatial variability, and complex failure mechanisms cannot be effectively captured by simplified linearized methods. The combination of Monte Carlo and Subset Simulation thus allows for more robust reliability assessment, enhancing the accuracy of design decisions and improving the overall safety and cost efficiency of deep foundation projects.

Studies have demonstrated the effectiveness of the probabilistic approach in pile foundation analysis. Liu & Yi [2] showed that the spatial correlation distance of soil parameters directly influences the probability of pile foundation failure. Golafzani et al. [10] emphasized that the use of Monte Carlo Simulation (MCS) with repeated random distributions can realistically represent the bearing capacity behavior of foundations under soil and load variability. A reliability-based probabilistic approach was also applied by Ushakova [11] and Liu et al. [3] to assess the foundation’s resistance to variations in soil strength.

Liu et al. [3] developed a reliability-based analysis framework for pile foundations by incorporating the stochastic nature of the setup effect, which represents the time-dependent increase in pile capacity after installation. Their study demonstrated that accounting for the randomness of the setup effect leads to a more accurate estimation of long-term pile performance and a better understanding of the probabilistic behaviour of axial resistance. This approach allows engineers to predict not only the mean load-carrying capacity but also the associated probability of failure, providing a more realistic and risk-consistent design basis for pile foundations under varying site conditions.

Similarly, Wen et al. [12] applied a comparable probabilistic approach to pile-reinforced slope systems, emphasizing the significance of soil–structure interaction and uncertainty in the mechanical behaviour of reinforced slopes. By integrating stochastic modelling into the slope stability analysis, their research highlighted that the inclusion of variability in soil strength parameters and pile resistance substantially improves the reliability evaluation of reinforced slope systems.

Furthermore, Lin [13] and Yao et al. [7] emphasized the growing necessity to update and refine reliability-based design (RBD) frameworks in geotechnical engineering practice. With the increasing complexity of environmental loading conditions, such as climate-induced variability, seismic effects, and groundwater fluctuations, along with the inherent spatial variability and uncertainty of field data, traditional deterministic and semi-probabilistic design methods are no longer sufficient. They recommended that modern reliability-based approaches should incorporate advanced probabilistic simulations, improved data interpretation techniques, and site-specific statistical calibration to ensure that foundation and slope designs remain both safe and economically optimized under uncertain geotechnical conditions.

Research has also shown that reliability-based analysis can serve as an important tool in foundation

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design decision-making. The study by Nogueira et al. [14] emphasized that traditional safety factors are no longer sufficient to ensure foundation system reliability. Winkelmann et al. [15], highlighted the importance of applying quantitative methods in assessing geotechnical risks to optimize design outcomes without incurring excessive construction costs.

In Indonesia, the application of probabilistic approaches in foundation design remains relatively limited; most designs still rely on deterministic empirical correlations between SPT-N values and bearing capacity, which often neglect the spatial variability and model uncertainty [6], [16]. Recent international studies indicate that integrating reliability-based methods such as the Monte Carlo Simulation can reveal hidden failure probabilities and produce more realistic safety estimations without increasing construction costs. Proper implementation of probabilistic approaches can potentially improve efficiency in safety factor utilization and design optimization, as reported by several studies [1], [17], [3].

This study aims to analyse the reliability of bored pile foundations by considering the variability of SPT values using a probabilistic approach based on Monte Carlo simulation. The probability of failure (Pf) and reliability index (β) will be calculated to represent the level of risk associated with the bearing capacity of the foundation, presented in Figure 1. The results of this research are expected to contribute to the application of reliability analysis in the field of geotechnical engineering in Indonesia, particularly to improve safety, efficiency, and optimization in deep foundation design.

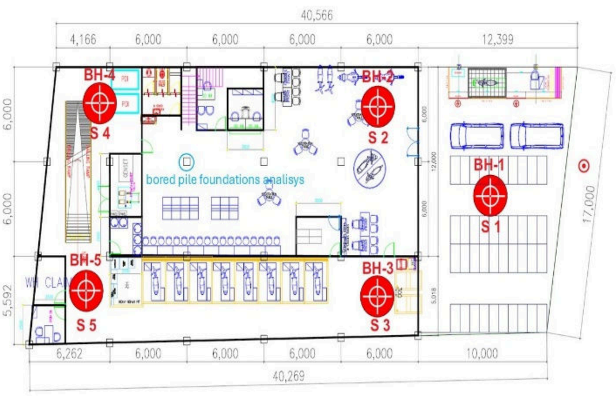

Figure 1. Drill points and boredpile locations analyzed

2. METHODOLOGY

This methodology section describes the steps undertaken to evaluate the reliability of bored pile foundations based on SPT data using a probabilistic approach with Monte Carlo Simulation (MCS). The methodology is designed to be reproducible, measurable, and applicable to field SPT data at various depths.

Deterministic Approach

The bearing capacity analysis of bored pile foundations is conducted based on field data obtained from the *Standard Penetration Test* (SPT). The N-SPT value is used to estimate both the end bearing capacity and the skin friction of the pile using an empirical approach that has been widely applied in foundation design practices in Indonesia [18].

The general equation [19], used to calculate the total ultimate bearing capacity (Q_{ult}) of bored pile foundations is expressed as follows Equation 1.:

$$Q_{ult} = \mu_b \times N_b \times A_b + \mu_s \times N \times A_s \quad (1)$$

where:

Qult	= ultimate bearing capacity of the pile (kN)
N_b	= SPT value at the pile tip
μb μs	= end-bearing & skin-friction coefficients
N	= average SPT value along the pile shaft
Ab	= cross-sectional area of the pile base (m²)
As	= surface area of the pile shaft (m²)

This approach separates the contributions of end bearing resistance (N_b) and skin friction resistance (N_r) according to the soil conditions derived from field Standard Penetration Test (SPT) results. The subdivision of these resistance components allows for a more accurate estimation of the total bearing capacity of bored pile foundations, as each mechanism responds differently to soil variability and stress distribution along the pile shaft.

The N-SPT values used in this analysis are obtained directly from field investigations and subsequently corrected to account for the effects of overburden pressure, depth, and local variations in soil stratigraphy, particularly around the pile tip zone where stress concentration is most significant. The correction process ensures that the derived SPT values represent the true in-situ resistance characteristics of the soil, minimizing bias caused by testing equipment, energy efficiency, or borehole conditions.

For the pile tip section, the corrected N-SPT value (N_b) is determined using Equation 2 below, which represents the average of two SPT readings taken immediately above and below the pile tip:

$$N_b = 0.5 \times (N_1 + N_2) < 40 \quad (2)$$

where:

N_1	= SPT value at the base or tip of the pile
N_2	= average SPT value from the pile tip to 4D
D	= diameter of the bored pile (m)

This correction approach follows standard geotechnical practice and ensures that the empirical correlation between SPT values and bearing capacity remains within the valid range of application. By refining the N-SPT data in this manner, the analysis achieves a more consistent and reliable estimation of both end bearing and skin friction contributions, forming the foundation for subsequent probabilistic and reliability-based evaluations of pile performance.

The evaluation of the Safety Factor (FS) is conducted to determine the margin of safety between the ultimate bearing capacity of the pile foundation and the applied working load. The allowable bearing capacity is calculated using Equation (3), which defines the ratio of the ultimate capacity to the required factor of safety. This relationship ensures that the design remains within acceptable limits of stability and serviceability under expected loading conditions.

$$Q = \frac{Q_{ult}}{FS} \tag{3}$$

The FS value is set between 2.5–3.0 according to SNI 8460:2017 [20].

Probabilistic Approach

The deterministic calculation results described earlier serve as the foundation for the probabilistic analysis, which aims to estimate the uncertainty in bearing capacity arising from the variability of N-SPT values and soil parameters. Probability distributions for the parameters Nb, N, μb, and μs are defined based on statistical analysis of field and laboratory data. The Monte Carlo simulation technique is then applied to incorporate these uncertainties into the reliability evaluation through the following procedure:

1) Randomly sample the values of N_b, N, μs, and μb according to their respective probability distributions (e.g., normal, lognormal, or uniform), as derived from experimental data.
2) Calculate the ultimate bearing capacity (Qult) for each iteration using the empirical equations presented in the deterministic analysis.
3) Determine the limit function as G(x) = R(x) - Q(x), where R(x) represents the resistance (capacity) and Q(x) denotes the applied load.
4) Estimate the probability of failure (P_f) as the ratio of the number of simulations where G(x) < 0 to the total number of iterations.
5) Calculate the reliability index (β) using the relationship $\beta = -\Phi^{-1}(P_f)$, where Φ^{-1} is the inverse of the standard normal cumulative distribution function.

A large number of simulations (typically 10,000–100,000 iterations) are conducted to ensure statistical convergence and stability of the results. The obtained β and P_f values are then used to quantitatively assess the safety level of the bored pile foundation.

This probabilistic approach allows for a more realistic representation of soil variability and load uncertainty compared to deterministic methods, thereby providing a comprehensive and quantitative framework for evaluating the reliability and performance of deep foundation.

The concept of the reliability index for the fundamental case (R, Q), are normally distributed through random variables. Safety is defined by the condition M > 0, while failure is defined as M < 0. The reliability index is the closest distance to M = 0. The Cornel equation μM = βσM is also shown in Figure 2.

The safety provided by the pole is described by the probability of failure, P_f, which is defined as the probability that the resistance R is less than the load Q, or the probability of failure (P_f) = P(R<Q), which is written as equation 4.

$$P_f = 1 - \phi\left(\frac{\mu M}{\sigma_{zM}}\right) \tag{4}$$

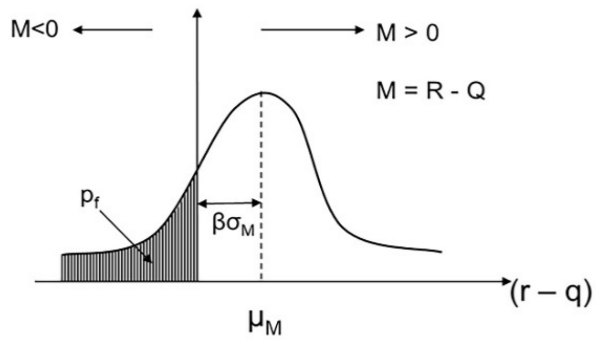

Figure 2. Reliability index: R and Q normal

Using the Advanced First Order Reliability Method, the reliability index (β) can be obtained as follows Equation 5. and Equation 6.

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{5}$$

$$\sqrt{\sigma_R^2 + \sigma_Q^2} = \sigma_M \tag{6}$$

Load Position on A Pile Group

The layout of the pile group is presented in Figure 3, developed based on the design of the permanent load acting on the structure. The pile group is designed to support an axial load of P = μP = 4000 kN with a standard deviation σP = 400 kN, as well as bending moments of μMy = 500 kN·m and μMx = 500 kN·m, transferred from the column of a five-story building including the rooftop. This configuration ensures that the axial and moment

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loads are properly distributed through the pile cap and transmitted to the underlying soil layers. The design also considers possible variations in load transfer and soil stiffness to maintain the stability and uniform performance of the foundation system. The pile group arrangement thus forms the basis for further deterministic and probabilistic analyses of foundation reliability under varying soil conditions.

The analysis of the load distribution and support reaction for each individual pile within the group is obtained using Equation (7) and Equation (8). These equations are employed to determine the proportion of axial load and moment resisted by each pile, taking into account the effects of pile spacing, group geometry, and interaction between piles.

$$\mu_Q = \mu_P + \mu_{My} + \mu_{Mx} \quad (7)$$

$$\sigma_Q = \sqrt{(\sigma p)^2 + \left(\sigma_{M_y} + \sigma_{Mx}\right)^2} \quad (8)$$

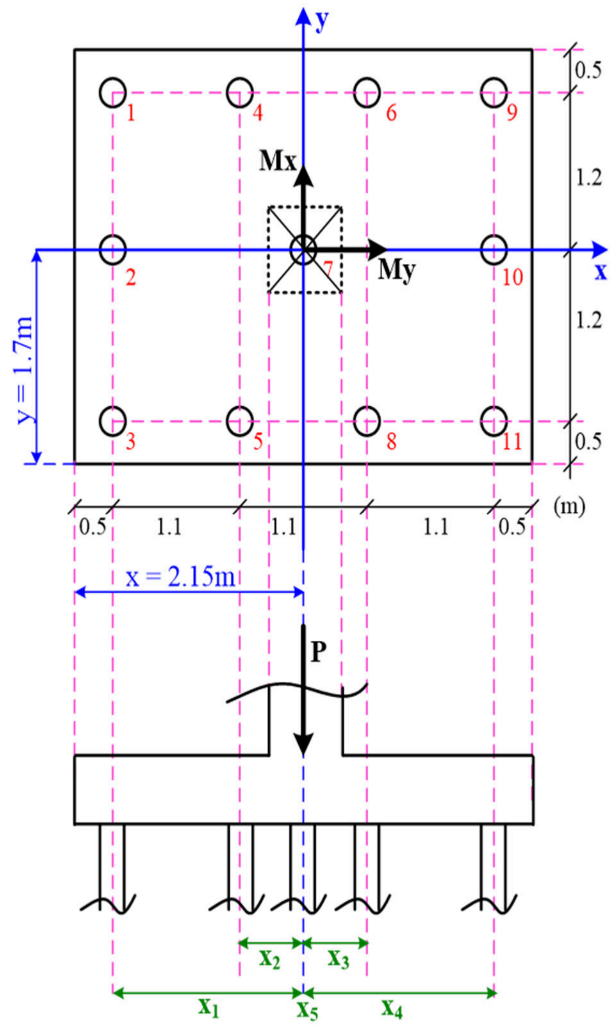

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Figure 3. Load position on a pile group

Preparation of SPT Data and Initial Statistics

The results of the Standard Penetration Test carried out by drilling 5 points in the field show N_{SPT} results as presented in Figure 4.

The figure illustrates the distribution of N-SPT values with soil depth at five borehole locations (BH1–BH5). The N-SPT values are used to identify the relative strength and density of the soil at each layer. In general, the N-SPT values increase with depth, indicating that the soil becomes denser at deeper layers. The $N_{average}$ line represents the average N-SPT value across all boreholes, showing a gradual increase in soil density with depth. The groundwater table is observed at a depth of approximately 5 m below the ground surface.

Based on these results, it can be concluded that the subsurface conditions at the study site are generally suitable for deep foundations, with a dense to hard bearing layer encountered at depths ranging from 6 to 25 meters.

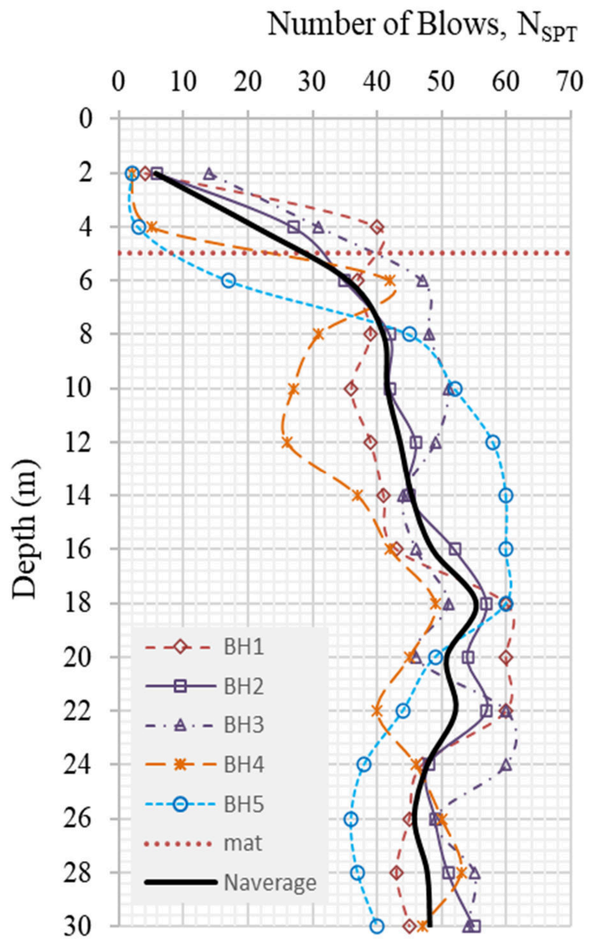

Figure 4. Variation profile

The Monte Carlo simulation method was employed in this study to account for the variability and uncertainty of soil parameters in the estimation of the ultimate pile capacity and overall system

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reliability. The basic procedure of the simulation can be summarized as follows:

1) Randomly derive the values of N_b (base resistance) and Nr (shaft resistance) using the statistical distribution parameters obtained from experimental or field data, then calculate the ultimate resistance R = Qult.
2) Randomly generate the load Q based on a predefined probability distribution function.
3) Calculate the mean resistance using the expression, $\mu R = \mu N_b + \mu N_r$, seen in the Equation 9.
4) Compute the standard deviation of resistance as Equation 10.
5) Perform an iterative process to update and refine the value of μR until statistical convergence is achieved.
6) Repeat steps (1) to (5) for a sufficiently large number of iterations (typically >10,000) to ensure the stability of the probability distribution
7) Finally, calculate the probability of failure (P_f) using Equation 4, based on the number of simulations where the resistance R is less than the applied load Q.

$$\mu_R = 40\ N_b \times Ab + 0.2 \times N_r \times A_s \quad (9)$$

$$\sigma_R = \sqrt{(\sigma_{Bb})^2 + \left(\sigma_{fric} + \sigma_{coh}\right)^2} \quad (10)$$

3. RESULTS AND DISCUSSION

The analysis results presented in Figure 5 illustrate the relationship between the Deterministic Factor of Safety (SF_Deterministic), Reliability (R_0), and the Probability of Failure (P(f)). The deterministic safety factor values are plotted against the system's reliability level to evaluate the extent to which deterministic analysis results can represent probabilistic conditions.

Figure 5 shows that the value of the deterministic factor of safety ($SF_{Deterministic}$) increases with increasing R_0, indicating a positive relationship between the two variables. The regression equation between SF and R_0 yields an R^2 value of 0.9212, suggesting that approximately 92.12% of the variation in the safety factor can be explained by changes in the reliability level. This relationship is illustrated by the solid curve.

Conversely, the probability of failure (P(f)) exhibits an opposite trend with respect to R_0. The P(f) value decreases sharply as R_0 increases, consistent with the fundamental reliability concept that a higher system reliability corresponds to a lower probability of failure. The dashed curve represents this relationship, with the same coefficient of determination (R^2 = 0.9212), indicating a mathematical interdependence between P(f) and R_0.

The threshold value of SF = 1 (green dashed line) represents the equilibrium boundary between safe and unsafe conditions. The analysis indicates that the intersection between the deterministic SF curve and SF = 1 occurs at R_0 = 0.52, corresponding to a probability of failure P(f) ≈ 0.48. This implies that when the deterministic safety factor equals unity, the system still has a 48% chance of failure and a 52% reliability level.

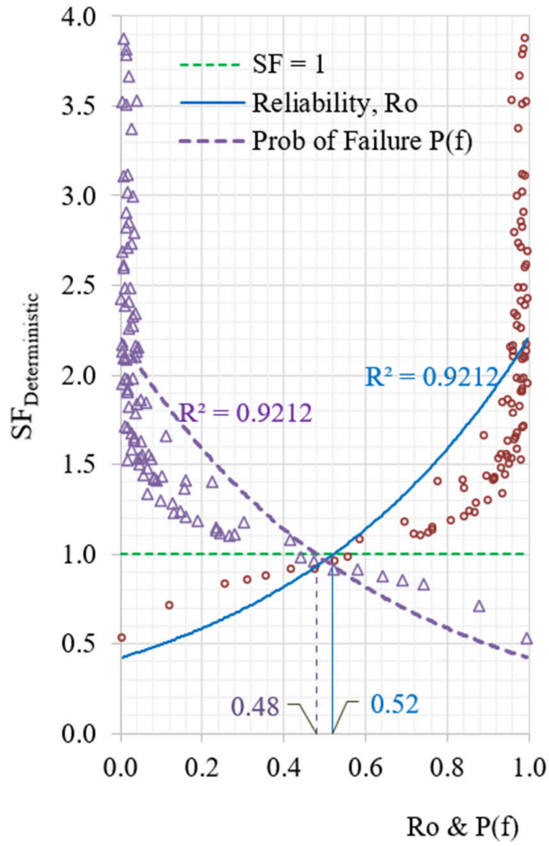

Figure 5. The Relationship between deterministic factor of safety, reliability, and probability of failure

These findings suggest that a deterministic analysis with SF = 1 does not fully ensure safety. Therefore, a reliability-based approach is required to better capture the uncertainty of soil parameters and field variability. The integration of deterministic and probabilistic analyses provides a more comprehensive basis for assessing geotechnical failure risk.

Figure 6 illustrates the relationship between the Reliability Index (β), Reliability (R_0), and the Probability of Failure (P(f)). This graph is used to evaluate the system's reliability level and the safety threshold of a geotechnical condition based on a probabilistic approach. The analysis results show that the value of β increases with increasing R_0, indicating that a higher system reliability corresponds to a

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greater reliability index. Conversely, the Probability of Failure (P(f)) exhibits an opposite trend to both β and R_o. These results are consistent with the fundamental principle of reliability analysis, where β represents the distance between the mean state and the limit state of failure

The reliability index limit (β = 0.05) serves as the minimum threshold distinguishing safe and unsafe conditions. The analysis results indicate that the intersection between the Reliability (R_o) curve and the Probability of Failure (P(f)) occurs at R_o = 0.52 with P(f) = 0.48, corresponding to β ≈ 0.05. This finding implies that a deterministic analysis with SF = 1 does not fully ensure safety, as the system is in a marginal (limit) state, where the probability of failure remains relatively high (48%) despite a reliability level of 52%. Hence, the condition cannot be considered fully safe from a probabilistic perspective.

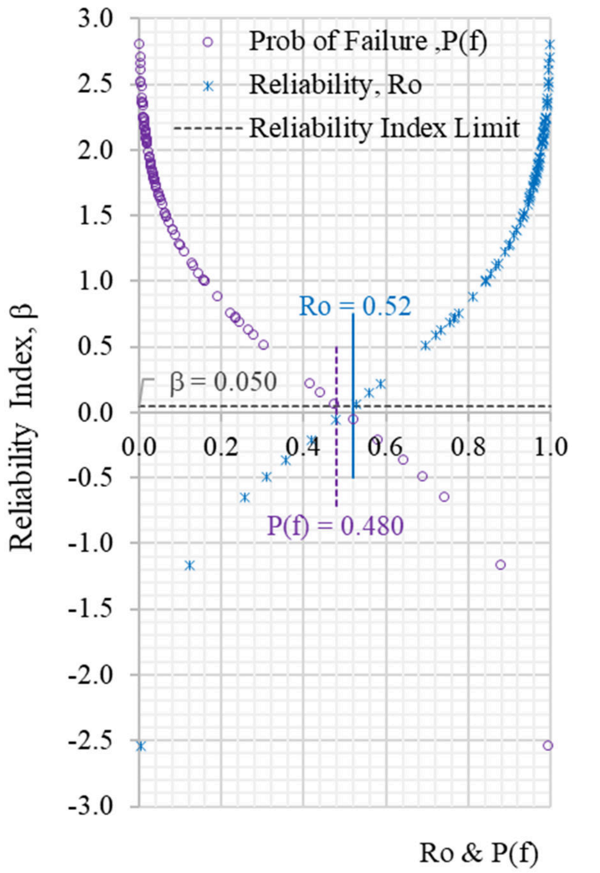

Figure 6. The Relationship between reability index, reliability and probability of failure

Figure 7 illustrates the relationship between the Reliability Index (β) at each borehole location (BH1–BH5) for four bored pile diameter variations, namely D = 0.3 m, 0.35 m, 0.4 m, and 0.5 m. This graph is used to evaluate the effect of pile diameter variation on the reliability level of the foundation system at each borehole location based on a probabilistic approach.

For the pile diameter of D = 0.3 m, β values range from 0.1 to -2.5, indicating that piles with smaller diameters exhibit lower reliability and even experience failure at BH4 and BH5 (β < 0.05). Meanwhile, for D = 0.35 m, β values fluctuate around the safety threshold, indicating a marginal or near-failure condition.

An increase in pile diameter shows a significant positive impact on the system's reliability. For D = 0.4 m and D = 0.5 m, β values increase substantially, ranging from 1.0 to 2.0, indicating that the system is in a probabilistically safe condition across all borehole locations. This finding demonstrates that increasing the pile diameter enhances stability and reduces the risk of failure due to the variability of soil parameters.

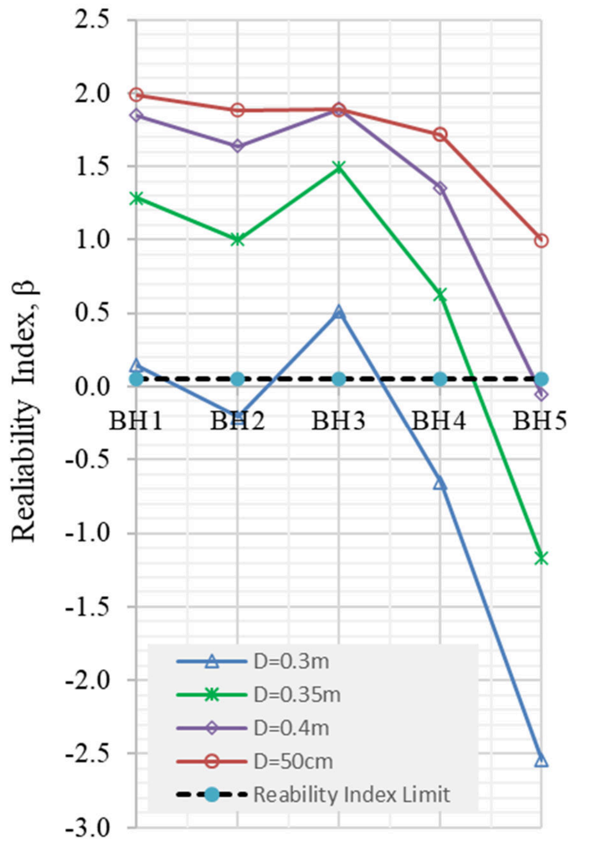

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Figure 7. The Relationship between reability index and diameter of bored pile

Figure 8 illustrates the relationship between the Deterministic Safety Factor (SF_Deterministic) and the Reliability Index (β) obtained from the probabilistic analysis. This graph is used to evaluate the extent to which the deterministic approach can represent the reliability level of a deep foundation system under soil parameter uncertainty.

In the figure, the horizontal line at SF = 1.0 represents the deterministic safety threshold, while

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the vertical line at β ≈ 0.05 indicates the probabilistic safety limit. The intersection of these two lines defines a marginal or borderline condition, representing the transition between safe and failure states. This intersection point signifies that the system is in a state of equilibrium between stability and potential failure

The analysis results demonstrate that the deterministic approach based on SF does not fully capture the actual reliability condition of the foundation system. Although SF = 1 is conventionally considered safe, it may still correspond to a significant probability of failure when soil parameter variability is high.

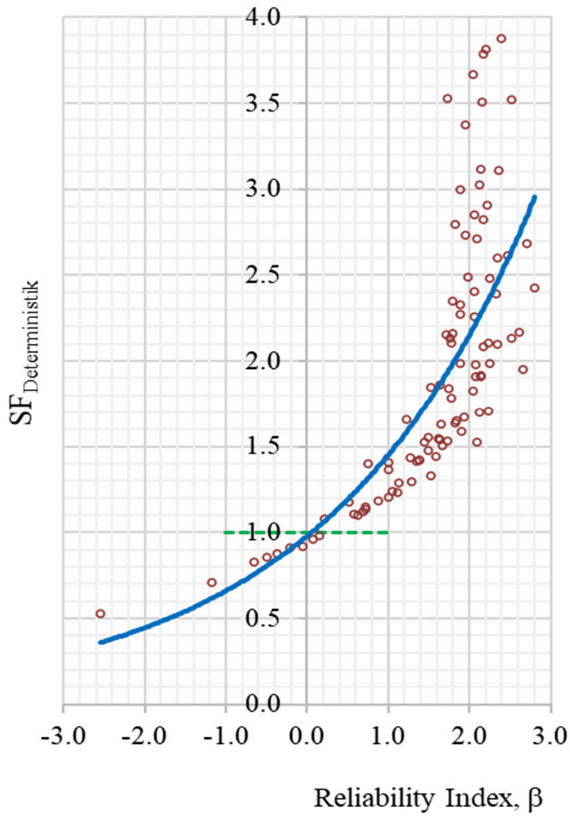

Figure 8. The Relationship between the deterministic safety factor and the reliability index

Therefore, the adoption of a Reliability-Based Design (RBD) approach is essential for deep foundation analysis. This method provides a more realistic and quantitative evaluation of structural safety by incorporating load uncertainty, soil variability, and field conditions, leading to a more reliable and accurate foundation design compared to conventional deterministic methods.

Practical Implications

The study results highlight several key implications for bored pile foundation design and field implementation:

1) Diameter of bored pile optimization increasing the pile diameter significantly improves the reliability index (β) and reduces the probability of failure. Larger diameters (≥ 0.4 m) are recommended in variable soil conditions to ensure adequate safety.
2) Consideration of soil variability the variation of β across boreholes indicates non-uniform soil conditions. Hence, reliability-based design should be applied instead of relying solely on deterministic safety factors.
3) Adaptive safety factors a reliability-based design factor (RBD) should be adopted, adjusting safety levels according to soil conditions, particularly where β < 0.05.
4) Field quality control Locations with low β require strict construction supervision to reduce variability and maintain design reliability.
5) Design and risk management Insight the findings emphasize the need for probabilistic design approaches in critical geotechnical projects to achieve a better balance between safety, cost efficiency, and uncertainty.

4. CONCLUSION

Based on the analysis of the relationships among the Probability of Failure (P(f)), Reliability (R_0), Reliability Index (β), and the Deterministic Factor of Safety (SF_Deterministic), several important conclusions can be drawn as follows:

1) The relationship between deterministic and probabilistic analyses shows a significant difference. Although a deterministic safety factor of SF = 1 is generally considered as the safety threshold, the probabilistic analysis reveals that under this condition, the system still has a failure probability of approximately 48% and a reliability level of only about 52%, indicating a marginal or near-limit state.
2) The reliability index limit (β = 0.05) serves as the minimum threshold separating safe and unsafe conditions. Systems with β < 0.05 exhibit a high probability of failure and require an increase in safety factor or a revision of the design.
3) An increase in pile diameter has a positive effect n system reliability. Higher β values observed in piles with larger diameters (≥ 0.4 m) indicate improved reliability and reduced failure risk due to soil parameter uncertainty, whereas smaller piles (≤ 0.35 m) show lower reliability and a greater tendency toward failure.
4) The reliability-based approach provides a more realistic representation than deterministic analysis. By accounting for the variability of soil properties and load uncertainties, the probabilistic approach more accurately reflects the actual

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safety level of the foundation system and can serve as a foundation for implementing Reliability-Based Design (RBD) in geotechnical engineering practice.

5) The relationship between $SF_{Deterministic}$ and β reinforces for a reliability-based framework. Although an SF value of 1.0 is commonly accepted as the safety limit, the corresponding β ≈ 0.05 indicates a borderline condition between safety and failure. This result confirms that deterministic calculations alone cannot fully capture the true reliability of the foundation system.

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This work represents a part of the author's academic journey and is expected to contribute to the advancement of knowledge, particularly in the field of geotechnical engineering and foundation reliability analysis.

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