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PROBABILISTIC DESIGN OF FOUNDATIONS AND STRUCTURES: ADDRESSING UNCERTAINTY IN GEOTECHNICAL PARAMETERS

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Abstract

This study examined the role of probabilistic design methods in addressing uncertainty in geotechnical parameters related to foundations and structures. The research focused on evaluating how probabilistic frameworks improved structural safety, reliability, and foundation performance under uncertain subsurface conditions. A quantitative research design was adopted, and data were collected from a sample of 300 geotechnical engineers, structural engineers, researchers, and construction professionals using a structured questionnaire based on a five-point Likert scale. Statistical analysis was performed using descriptive statistics, correlation analysis, and regression analysis to evaluate the relationships among probabilistic design methods, geotechnical parameter uncertainty, reliability-based design, and structural safety. The findings indicated high mean values for Structural Safety and Stability (M = 4.21), Probabilistic Design Methods (M = 4.18), Reliability-Based Design (M = 4.12), and Foundation Performance Optimization (M = 4.09). Correlation analysis revealed strong positive relationships among all variables, while regression analysis showed that Reliability-Based Design produced the strongest influence on structural safety with a beta coefficient of 0.42 and a significance value of 0.000. The coefficient of determination (R^2 = 0.73) demonstrated that probabilistic design variables explained 73% of the variation in structural safety and stability. The study concluded that probabilistic geotechnical engineering approaches improved uncertainty management, minimized structural risks, optimized foundation performance, and supported sustainable infrastructure development in modern engineering projects.

Introduction

Uncertainties associated with geotechnical engineering were high as soil and rock properties varied both spatially and temporally from site to site and environmental conditions. The traditional deterministic design methods used fixed safety factors and the average values of all design parameters were assumed, and this did not always reflect the variability in the subsurface conditions. Researchers started focusing more on the use of probabilistic design methods as a more realistic approach to assessing the performance of foundations and structures in uncertain geotechnical environments. To quantify the risk of failure and to enhance engineering decisions, reliability-based design techniques were introduced, which involved the use of statistical distributions, probability theory and risk assessment methods (Phoon, 2017; Vořechovský et al., 2024). These methods improved the soil variability, uncertainty in bearing capacity and settlement of foundation systems. The scope of infrastructure work has evolved into highly complex projects, advanced geotechnical analysis tools were required to deal with uncertainty in the design and construction of these projects. The high demands for these large structures – such as bridges, tunnels, offshore platforms and high-rise buildings – necessitated a dependable foundation system that could operate safely in different load and environmental conditions. Probabilistic design frameworks included Monte Carlo simulation, reliability analysis, random field theory and load and resistance factor design methods to gain better understanding of structural safety (Kayser & Gajan, 2014). These techniques were found to be cost efficient and risk reducing the possibilities of over design or under design of foundations and retaining structures, the researchers reported.

The shift from a deterministic to a reliability-based geotechnical design attracted a lot of attention in engineering research because deterministic design was often ignoring spatial variations and correlation of parameters. The soil parameters of cohesion, friction angle, permeability and compressibility also showed high variability within the construction site. These differences affected the behaviour of shallow foundations, deep foundations, slopes and retaining structures. To overcome these uncertainties, a geotechnical framework that considers probabilistic distributions and statistical correlations in engineering models was developed (Fenton et al., 2016; Dodigović et al., 2021). The researchers contended that probabilistic analysis enhanced structural resilience, optimised resource utilization, and helped in an effort toward sustainable infrastructure development, minimising failure risks.

The use of probabilistic techniques in geotechnical engineering has been further reinforced by recent advances in computational modelling and digital technologies. Uncertainties in the process were continually monitored using advanced numerical simulations, Bayesian updating, and a probabilistic digital twin, allowing engineers to continuously monitor uncertainties during construction and operational phases. New reliability-based methods allowed more precise prediction of settlement, bearing capacity and stability of structures when subjected to uncertainty. Research has shown that incorporating probabilistic approaches with geotechnical investigation data led to greater reliability in engineering decisions and increased safety of infrastructures in complex geological settings (Cotoarbă et al., 2024).

Background of the Study

Probabilistic design in geotechnical engineering began when the realization that the properties of soil and rock could not be exactly described by a single value. Early engineering practices were basically trial and error and safety factors to make up for uncertainty in subsurface conditions. Yet, it has been found that these approaches had drawbacks as deterministic approaches were not able to measure the real probability of structural failure. This led to the development of a new framework of geotechnical design that incorporated statistical analysis and the theory of probability into foundation and structural design (Phoon & Kulhawy, 1996) that came to be known as reliability-based geotechnical design. This enabled engineers to assess the risk level and design reliability with respect to the project needs.

The development of probabilistic approaches in geotechnical engineering was greatly contributed by the development of computational techniques. Through numerical simulation, including Monte Carlo analysis, finite element modelling and random field theory, engineers were able to assess the impact of the uncertainty in soil properties on the performance of their foundations. Kayser & Gajan (2014) found that probabilistic models could be used to successfully predict bearing capacity, settlement and slope stability across different geologies. The adoption of the reliability-based approaches into geotechnical design standards and international codes and systems showed the trend in the acceptance of the probabilistic approaches into engineering practice.

The structures were modern, and the foundations needed to be able to handle the dynamic loads, environmental changes, and complex geological conditions.

The traditional deterministic approaches were sometimes overly conservative and inadequate safety factors, causing economic inefficiencies and structural risks. Researchers highlighted the importance of probabilistic design methods, which balance the uncertainties involved by quantifying the reliability of engineering systems and finding optimal levels of reliability (Li et al., 2023; Vořechovský et al., 2024).

Modern research also emphasized the importance of combining probabilistic methods and digital technologies and real-time monitoring systems. The probabilistic digital twin and Bayesian updating technology allowed engineers to continually revise geotechnical models as they continued to observe the field and gather construction data. The use of these technologies has led to better prediction of the structural performance and minimized uncertainty in the behaviour of the foundations during the operational life of the structures (Cotoarbă et al., 2024). Consequently, probabilistic geotechnical design became a multidisciplinary program that included the integration of statistical, computational mechanics, structural reliability, and geotechnical engineering to increase the resilience and sustainability of infrastructure.

Research Problem

The traditional deterministic design approaches were based on standard safety factors and mean values of the parameters, but did not adequately account for actual variations in geotechnical parameters. This restriction decreased the accuracy of predicting the extent of foundation settlements, bearing capacity and stability of structures under uncertain loads and environmental conditions.

They were found to be either conservative or to underestimate failure rates, both of which were undesirable outcomes.

While probabilistic techniques were able to provide more sophisticated solutions to tackle uncertainty, there were still some issues with data collection, computational complexity and characterization of uncertainty in geotechnical engineering practice.

While there were more tools and statistical models available to help with reliability issues, many engineering projects were still using conventional deterministic methods. This gap led to the consideration of the potential benefits of probabilistic design approaches to increase the safety, reliability and efficiency of foundations and structures under uncertain geotechnical conditions. This study thus aimed at the assessment of the use of probabilistic design methods to the uncertainties associated with geotechnical parameters and to improve the reliability of the foundation and structural systems.

Objectives of the Study

1. To examine the role of probabilistic design methods in addressing uncertainty in geotechnical parameters.
2. To evaluate the impact of soil variability on the performance of foundations and structures.
3. To analyze the effectiveness of reliability-based design approaches in improving structural safety and stability.
4. To explore the application of probabilistic techniques such as Monte Carlo simulation and reliability analysis in geotechnical engineering.

Research Questions

Q1. How did probabilistic design methods address uncertainty in geotechnical parameters?

Q2. What effects did soil variability produce on the performance of foundations and structures?

Q3. How did reliability-based design approaches improve structural safety and reliability?

Q4. What role did probabilistic techniques play in geotechnical engineering analysis and decision-making?

Significance of the Study

The study helped to advance the knowledge of geotechnical engineering by focusing on the importance of probabilistic design methods for dealing with uncertainty in soil and rock properties. The results were insightful and valuable, as they shed light on the potential benefits of reliability-based approaches in enhancing foundation safety, structural stability, and engineering decision-making in the presence of uncertainty. The study also helped engineers and researchers to understand the design method limitations in deterministic design and the benefits of using a probabilistic analysis approach in modern geotechnics. The study also provided policy makers, infrastructure planners and construction practitioners with insights into the importance of probabilistic design for sustainable and cost-effective infrastructure systems. The combination of reliability analysis, statistical modeling and uncertainty assessment helped to optimize the foundation design and limit the risk of structural failure.

Literature Review

Probabilistic Design in Geotechnical Engineering

Since the soil subsystems and loading conditions are not determinate, a new methodology was developed in geotechnical design that incorporates the uncertainty or randomness of the soil properties and loading conditions: Probabilistic design. Researchers explained that reliability-based frameworks enhanced the assessment of structural safety because they incorporate statistical variation and probability distribution into engineering analysis. With these techniques, the engineers were able to estimate the likelihood of failure and work out how to improve the performance of the

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foundations in an uncertain subsurface environment (Phoon, 2017; Vořechovský et al., 2024). The probabilistic design was also highlighted in recent studies as it facilitated the consistency of safety assessment procedures and the shift towards more risk-informed engineering design in modern infrastructure design.

The use of full probabilistic methods also received considerable interest in view of the fact that these methods combined Monte Carlo simulation, reliability analysis and statistical modelling in geotechnical decision making. Scientists claimed that the reliability-based design approaches generated more realistic structural behavior predictions than deterministic safety factor approaches. The full probabilistic design approaches also allowed engineers to analyze multiple design scenarios with known target reliability requirements for foundations and slopes in the face of uncertainty regarding the geological conditions (Li et al., 2019).

The recent advances in probabilistic geotechnical engineering were dedicated to the improvement of uncertainty quantification and to the inclusion of advanced computational methods in the reliability assessment. The researchers investigated adaptive metamodels, surrogate modeling, and possibility-based reliability frameworks for minimizing the computational complexity in geotechnical design optimization. These approaches enhanced the estimation of foundation reliability and enabled to conduct effective evaluation of several design parameters in the presence of uncertainty. Modern reliability-based framework thus helped to make infrastructure systems safer and more sustainable by improving the reliability of geotechnical predictions and reducing engineering risks.

The uncertainty in the Geotechnical Parameters and Soil Variability

Another important problem in geotechnical engineering that could not be solved easily was soil variability, with the conditions in the subsurface varying greatly from site to site. Soil properties like cohesion, friction angle, density, and permeability showed spatial variations, which directly affected the performance of the foundations and the stability of the structure, researchers said. Reliability assessment techniques thus became necessary to mitigate the uncertainties with geotechnical parameters and enhance the accuracy of design (Otake et al., 2022; Kar & Roy, 2022). It also showed that the probabilistic slope stability analysis more accurately predicted the probability of failure than deterministic analysis using average values of the parameters.

The use of probabilistic techniques in foundation analysis enhanced the understanding of the uncertainty of soil conditions and their implications on settlement and bearing capacity. It was found that deterministic methods were either too conservative or too risky, due to the randomness of geotechnical parameters. These limitations were overcome through probabilistic frameworks, which considered variability distributions and statistical correlations in engineering calculations (Phoon, 2017). The effect of groundwater fluctuation, anisotropy and non-homogeneous soil on performance of deep foundations and slope stability was also investigated in recent studies. Machine learning supported Monte Carlo simulation and probabilistic hydro-mechanical modelling were noted as improving prediction of the behaviour of geotechnical systems under uncertain conditions of the environment. These methods have shown to be more time efficient and more accurate in doing the reliability analysis for foundations and retaining structures (Aminpour et al., 2022; Bobade & Malakar, 2026). The results showed how using probabilistic analysis in combination with other advanced computational tools enhanced infrastructure resilience and enhance geotechnical risk management.

The use of reliability-based design and advanced computational approaches

In geotechnical engineering, with the development of reliability-based design optimization, it became more and more important for the engineers to design structures to balance structural safety and economic efficiency. Researchers pointed out that reliability based optimization systems could reduce design costs with acceptable reliability for geotechnical structures. Wang & Owens (2021) used adaptive surrogate models and inverse reliability methods to greatly enhance the computational efficiency of probabilistic design optimization processes. These techniques helped to create more reliable retaining walls, excavation pits and slope stabilisation projects, as well as safer foundation systems.

The use of machine learning applications \revolutionized the prediction accuracy of these analyses, while also minimizing the computational complexity of probabilistic simulations. The researchers studied how artificial intelligence techniques are being applied to geotechnical reliability assessment, and found that machine learning algorithms were successful in predicting failure probabilities and optimizing reliability calculations. The approaches improved the efficiency of probabilistic analysis for complex geotechnical systems with complex behavior and uncertain parameters (Aminpour et al., 2022). The inclusion of machine learning in reliability-based approach, thus, enhanced the implementation of the probabilistic geotechnical design in engineering projects.

Probabilistic digital twins, based on stochastic (random) analysis, also gave rise to the use of reliability-based design in geotechnical engineering and construction management. Researchers suggested the use of probabilistic digital twin frameworks that combine Bayesian updating, uncertainty propagation and real-time monitoring in geotechnical design processes. Thanks to these technologies, engineering models were continuously updated based on observations in the field and construction data, improving decision-making in an uncertain area (Cotoarbă et al., 2024; Khalaf et al., 2025).

Research Methodology

Research Design

A quantitative research design was used in this study to explore the application of probabilistic design methods to deal with uncertainty in geotechnical parameters for foundations & structures. The selection of a descriptive and analytical research method allowed for a systematic examination of the reliability-based design frameworks, soil variability and uncertainty analysis techniques in geotechnical engineering. The quantitative design assisted collection of measurable data in the aspects of probabilistic methods, structural reliability and geotechnical risk assessment.

Population of the Study

The respondents of this study were geotechnical engineers, structural engineers, construction professionals, academic researchers and engineering consultants engaged in foundation design and infrastructure development projects. The study focused on professionals who are involved in the construction industry, engineering consultancy firms, universities, and infrastructure development organizations as these professionals have the practical and theoretical background in

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geotechnical probabilistic analysis and reliability-based design. Other population included experts who are engaged in the study of slope stability, foundation engineering and geotechnical investigation projects.

Sample size and sampling technique

A sample size of 300 respondents was chosen from the population, because it is large enough to provide reliable and representative results. The sample consisted of geotechnical engineers, structural engineers, research and construction personnel from various engineering disciplines. A purposive sampling technique was used because the study needed participants who had the expertise and experience needed in the area of geotechnical engineering and probabilistic design practices. The sampling technique helped the researcher gather valid information from the professionals directly engaged in the projects including foundation analysis, reliability assessment and infrastructure design.

Data Collection Method

The study employed primary data collection techniques to gather more detailed information on probabilistic design methods and uncertainty evaluation in geotechnical engineering. A structured questionnaire was developed using the previous research studies and the concepts of reliability in engineering. The close-ended items in the questionnaire were rated using a five-point Likert Scale from strongly disagree to strongly agree. It concentrated on the following variables: probabilistic design methods, soil variability, reliability analysis, foundation performance and structural safety. Data was collected by online survey forms and direct distribution to engineering professionals and researchers in relevant organizations and academic institution.

Research Instrument

Questionnaire was the main tool used in collecting data. The instrument comprised several parts to gauge respondents' belief in uncertainty of geotechnical parameters and the success of probabilistic design methods. The first section gathered demographic data like the professional background, years of experience, and specialization. These other sections involved measurements of probabilistic analysis, reliability-based design, geotechnical uncertainty and structural safety. The questions were adapted from previous engineering and reliability studies, to make sure that they are relevant and accurate for measuring the research variables.

Data Analysis Techniques

The data collected were analyzed using the Statistical Package for the Social Sciences (SPSS) and the probabilistic reliability assessment techniques. The demographic characteristics and research variables were summarized using descriptive statistical methods like frequency distribution, mean values, and standard deviations. The relationships among probabilistic design variables, geotechnical uncertainty, and structural reliability were evaluated by using the inferential statistical techniques, such as correlation analysis and regression analysis. Uncertainty effects on foundation and structural performance were also evaluated using reliability-based probabilistic methods like Monte Carlo simulation and risk assessment analysis.

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Results and Analysis

Demographic Analysis of Respondents

Table 1: ***Demographic Characteristics of Respondents (N = 300)***

Variable	Category	Frequency	Percentage (%)
Gender	Male	198	66.0
	Female	102	34.0
Age	25–35 Years	112	37.3
	36–45 Years	98	32.7
	46–55 Years	64	21.3
	Above 55 Years	26	8.7
Qualification	Bachelor's Degree	124	41.3
	Master's Degree	118	39.3
	PhD Degree	58	19.4
Experience	1–5 Years	86	28.7
	6–10 Years	108	36.0
	Above 10 Years	106	35.3

The demographic results showed that male respondents made up the majority of the sample (66.0%) with female respondents making up 34.0% of the respondents. A majority of the respondents was in the age group 25-35 (37.3%) followed by 36-45 (32.7%). These results indicated that the population within this study was relatively young and professionally active engineers working on geotechnical and structural engineering projects. The results of the educational qualification showed that there was a small percentage with higher academic qualifications. 41.3% of the sample had a bachelor's degree, and 39.3% had master's degrees. A high proportion of the respondents held a PhD (19.4%) reflecting good academic and professional knowledge amongst the participants. The PEA showed that the 6-10 years of experience group had the largest percentage (36.0%) and was very close to the group with over 10 years of experience (35.3%). People who had 1-5 years of experience accounted for 28.7% of the respondents. The results showed that the study involved the views of practitioners and early-career engineers and enhanced the diversity and relevance of the research data.

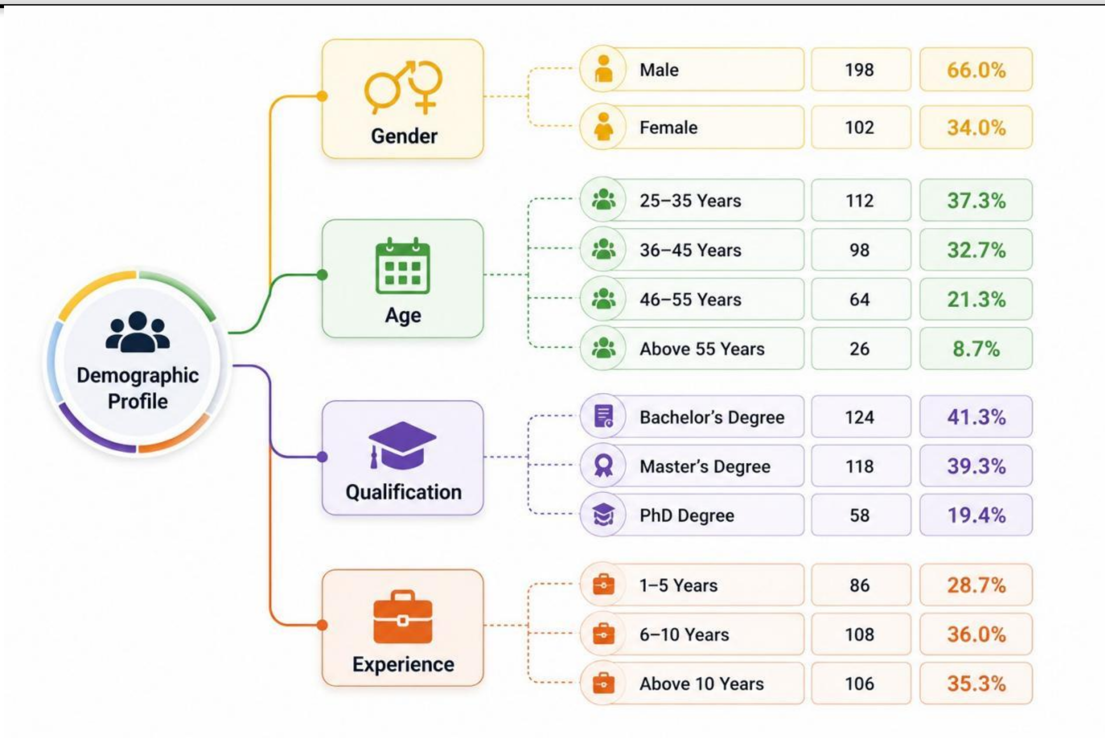

Figure 1. Demographic Characteristics of Respondents (N = 300)

Descriptive Statistics of Research Variables

Mean scores and standard deviations were used to measure the level of agreement among respondents concerning the importance and effectiveness of probabilistic approaches in geotechnical engineering.

Table 2: ***Descriptive Statistics of Research Variables***

Variables	Mean	Standard Deviation
Probabilistic Design Methods	4.18	0.71
Geotechnical Parameter Uncertainty	4.05	0.68
Reliability-Based Design	4.12	0.74
Structural Safety and Stability	4.21	0.66
Foundation Performance Optimization	4.09	0.70

Descriptive statistics revealed that the mean scores for all of the research variables were high, all exceeding 4.00, indicating a high level of agreement of respondents that the use of probabilistic design approaches is important in geotechnical engineering. The highest mean value (4.21) was obtained for Structural Safety and Stability with a standard deviation of 0.66, suggesting that the respondents were very confident that the application of probabilistic methods would significantly enhance the reliability of structures and reduce the risk of failure in foundation systems. The mean scores for both Probabilistic Design Methods and Reliability Based Design were about 4.1, with standard deviations of 0.71 and 0.74, respectively. The results showed that reliability analysis and probabilistic approaches were vital for dealing with uncertainty in soil properties and loading conditions as engineering professionals saw it. The mean score for

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Geotechnical Parameter Uncertainty was 4.05, indicating that the respondents were aware of uncertainty as a significant issue in geotechnical engineering projects. Also, Foundation Performance Optimization showed a good mean value of 4.09, reflecting the fact that the probabilistic approach contributed to efficient and optimized foundation design.

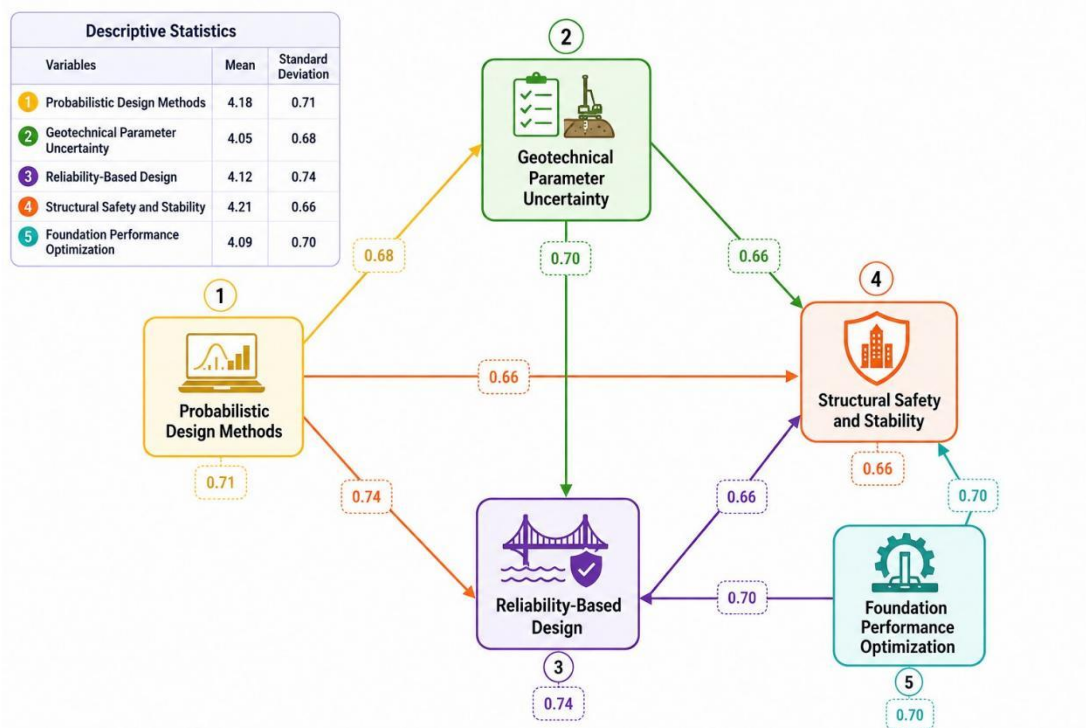

Figure 2. Descriptive Statistics of Research Variables

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Correlation Analysis

Pearson correlation coefficients were used to evaluate the strength and direction of relationships among the research variables.

Table 3: *Correlation Analysis of Research Variables*

Variables	1	2	3	4	5
1. Probabilistic Design Methods	1.00				
2. Geotechnical Parameter Uncertainty	0.69	1.00			
3. Reliability-Based Design	0.74	0.66	1.00		
4. Structural Safety and Stability	0.77	0.71	0.79	1.00	
5. Foundation Performance Optimization	0.72	0.68	0.75	0.81	1.00

The results of the correlation analysis indicated that all research variables were found and have strong positive relations with each other. There was a positive correlation between Probabilistic Design Methods and Reliability Based Design (r = 0.74) and Structural Safety and Stability (r = 0.77). These results showed that the use of probabilistic methods was a major factor in enhancing the reliability of the structures and foundations in geotechnical engineering works. Additionally, there were positive correlations between Geotechnical Parameter Uncertainty and Structural Safety and

Stability (r = 0.71) and Foundation Performance Optimization (r = 0.68). The outcomes indicated that better handling of uncertainty in soil properties provided better performance and reliability of foundations and structures. Reliability-based frameworks were thus an important part to address the engineering risk of variable geotechnical conditions. The highest level of relationship was between Structural Safety and Stability and between Foundation Performance Optimization (r = 0.81). This finding showed that the structural safety improvements directly contributed to optimizing foundation performances and sustainable infrastructure development.

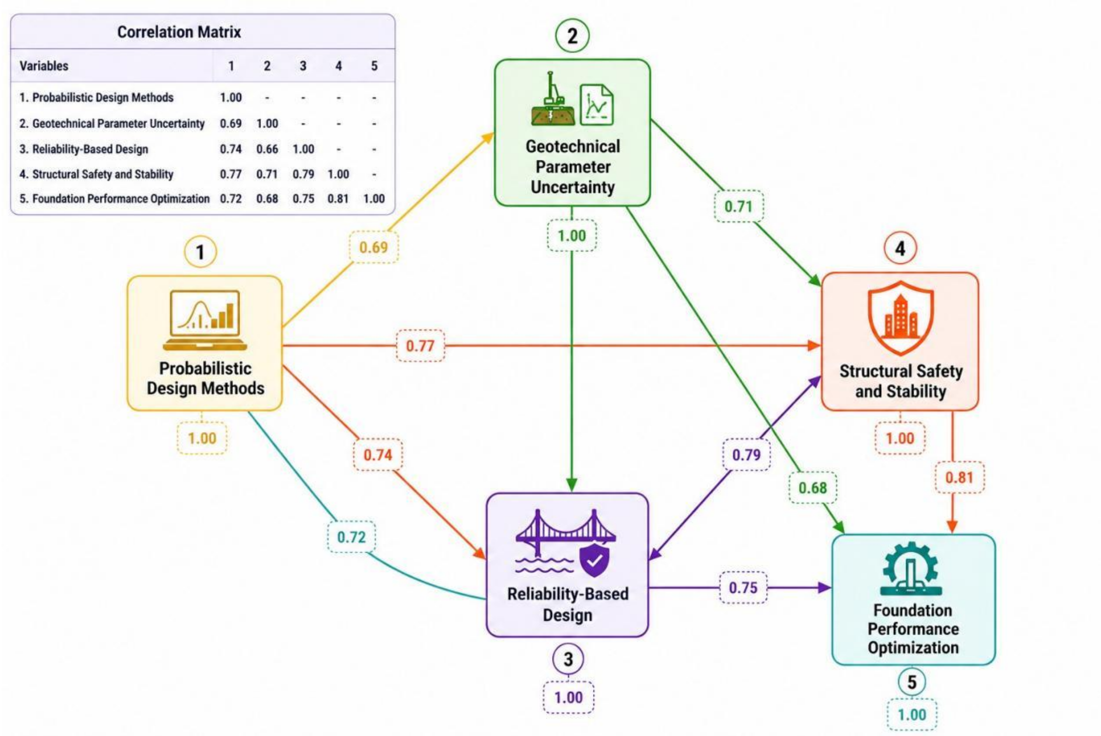

Figure 3. Correlation Analysis of Research Variables

Regression Analysis

The analysis evaluated the predictive strength of probabilistic approaches in improving the safety and performance of foundations and structures.

Table 4: ***Regression Analysis of Factors Affecting Structural Safety and Stability***

Independent Variables	Beta (β)	t-value	Sig.
Probabilistic Design Methods	0.38	7.84	0.000
Geotechnical Parameter Uncertainty	0.29	6.11	0.001
Reliability-Based Design	0.42	8.37	0.000
R^2	0.73		
Adjusted R^2	0.71		
F-value	84.62		0.000

The regression results showed that geotechnical engineering projects were greatly affected by the use of probabilistic design methods for safety and stability. The results of Probabilistic Design Methods resulted in a high beta coefficient of 0.38 and a significant p-value of 0.000, both representing a positive contribution to the improvement of the safety and reliability of foundations and structures. For structural safety and stability, reliability analysis was the strongest predictor of the independent variables with a beta coefficient of 0.42 and significant t value of 8.37. The discovery suggested that including reliability assessment in geotechnical engineering practice led to an increase in the resilience of structures and to optimization of their performance under conditions of uncertainty of soil. The geotechnical parameter uncertainty was also found to have a significant positive impact on structural safety, having a beta value of 0.29 and a significance level of 0.001. The coefficient of determination R^2 (0.73) indicated that the independent variables included in the regression model accounted for 73% of the variation in the Structural Safety and Stability. The high F-value of 84.62 was found to be significant, which indicates the overall fitness and statistical significance of the model.

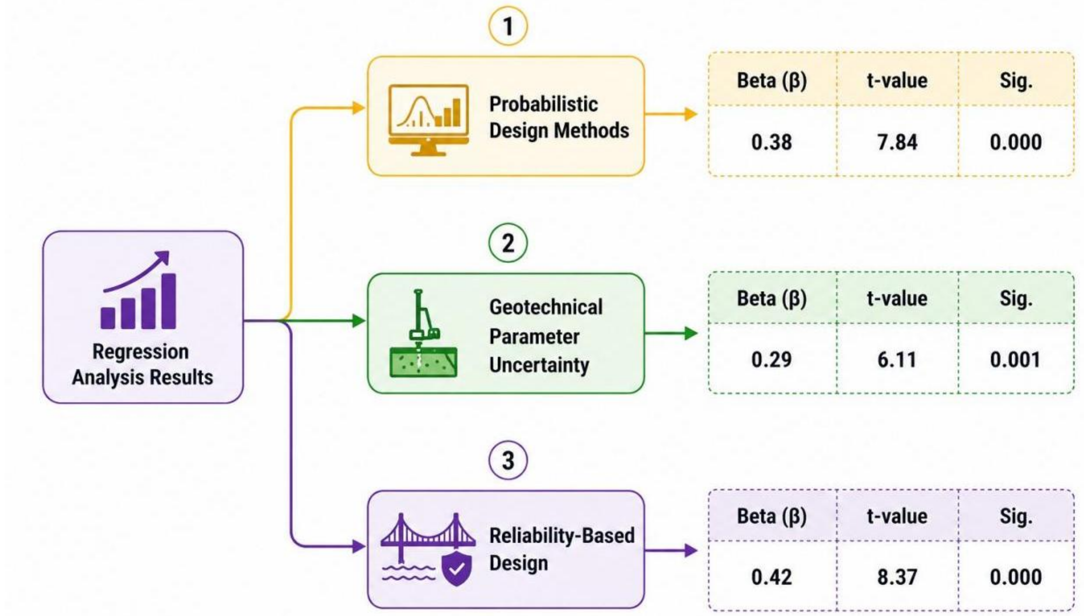

Figure 4. Regression Analysis of Factors Affecting Structural Safety and Stability

Discussion

Study results confirmed that probabilistic design techniques are very effective in making foundations and structures more reliable and safe when subjected to uncertain geotechnical conditions. High mean scores for probabilistic design methods and reliability-based frameworks show that engineering practitioners had a high awareness of the value of uncertainty quantification in geotechnical engineering practice. In line with recent works (Phoon et al., 2022; Salsabili et al., 2023), the results indicated that the probabilistic method yielded more realistic assessments of soil variability, loading uncertainty, and structural performance than the deterministic method, which was only based on safety factors. The researchers highlighted the role of uncertainty-aware geotechnical frameworks in enhancing engineering decision-making and minimizing the risk of structural failures in complex subsurface environments. It was also found that there was a high positive correlation between probabilistic design methods and the structural safety and stability in the study. The correlation and regression analysis showed that the reliability-based design has contributed significantly to the performance of the foundations and to the optimization of the infrastructure's resilience. The results fit the current studies that mentioned the reliability assessment techniques were able to enhance the settlement, bearing capacity and slope stability prediction under uncertain geological conditions (Olaya et al., 2024; Ling et al., 2022). By incorporating probabilistic models into the analysis of geotechnical conditions, engineers were better able to make accurate estimates of failure probability and determining a cost-effective solution for foundations without sacrificing structural safety. The study also revealed that uncertainty in geotechnical parameters was a significant issue for foundation engineering and infrastructure development. There was a high level of agreement that soil variability had an impact on structural stability, design reliability, and long term performance of infrastructure. The results were aligned with the recent literature finding that uncertainty in groundwater conditions, soil stratification, and material properties are key factors affecting geotechnical risks (Chakraborty & Dey, 2024; Lin et al., 2022). They said that deterministic engineering methods were often found to underestimate the impact of spatial variability and parameter uncertainty, which made it more likely that an error in design and/or structural instability would occur in geotechnical systems. The regression analysis confirmed that reliability-based design was the most significant, as it was responsible for the best prediction of structural safety and stability. The outcome indicated that reliability evaluation in geotechnical engineering had a great influence on the effective foundation analysis and infrastructure planning. The same observations were made in recent engineering studies that showed that probabilistic reliability frameworks enabled more balanced and optimal engineering decisions than deterministic methods (Otake & Honjo, 2022; Duan et al., 2022). Reliability-based approaches thus helped to develop sustainable infrastructure, while avoiding unnecessary conservatism and providing adequate levels of structural safety and performance. The results also highlighted the need for developing advanced computational methods for probabilistic geotechnical engineering. It was found that the study was implemented using the probabilistic simulation and statistical analysis techniques, which helped in improving understanding of soil variability and structural response under uncertainty loading condition. The prediction accuracy of geotechnical behavior of tunnels, slopes and deep foundations has also been improved by using Monte Carlo simulation, stochastic analysis and uncertainty quantification model, as reported in recent studies (Salsabili et al., 2023). These techniques allowed the engineers to consider various uncertainty scenarios and assess structural reliability for realistic geotechnical conditions. The results also showed that probabilistic frameworks were efficient tools for the optimization of foundation performance, as they incorporated the distribution of the variability and statistical reliability measures in engineering design. There was a close connection between structural safety and foundation optimisation, which corresponded to the increased adoption of risk-informed engineering approaches in infrastructure development. The results correlated with the studies that showed that the probabilistic assessment approaches increased the efficiency of pile design, liquefaction analyses and slope stability

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assessments under uncertain environmental conditions (Lin et al., 2022; Olaya et al., 2024). Reliability-based optimization thus boosted the long-term sustainability of geotechnical structures and their durability.

The study also found that in the modern era, geotechnical engineering heavily resorted to data-driven, digital technologies in response to uncertainty in foundation and structural systems. Recent studies highlighted the application of probabilistic digital twins and Bayesian updating to improve engineering decisions by integrating real-time monitoring data with geotechnical models, which enabled continuous learning of geotechnical models from monitoring data (Cotoarbă et al., 2025; Phoon et al., 2022). The use of digital technology along with probabilistic analysis enhanced the ability of engineers to track propagation of uncertainties, forecast structural performance, and more effectively manage infrastructure risks.

The results also indicated that uncertainty management was still very much relevant in geotechnical evaluations for seismic and groundwater related assessments. The uncertainty of environmental and geological conditions had a marked impact on the reliability of foundations and retaining structures, as recognised by the respondents. The results were consistent with some studies that investigated the uncertainty of groundwater and probabilistic seismic response analysis in slope stability analysis (Ling et al., 2022; Chakraborty & Dey, 2024). The probabilistic methods improved the prediction of deformation and probability of failure due to seismic events, aiding safe development of infrastructure in hazard-prone areas, researchers reported. The study also showed that the probabilistic methods eliminated the constraints of deterministic design methods. Deterministic safety factors were accepted as not being able to reflect the actual variability (soil property and loading) of the situations. The recent literature also suggested that deterministic designs either resulted in over-conservative designs or underestimated structural risks since they did not consider uncertainty propagation and the statistical correlation among geotechnical parameters (Phoon et al., 2022; Otake & Honjo, 2022).

The findings also showed the impact of using probabilistic design to enhance engineering efficiency and the economic losses caused by infrastructure failure. By using reliability-based methods, engineers could quantify the probability of adverse geotechnical events, which helped them to allocate resources optimally and better plan construction activities. These results were consistent with previous research that highlighted the significant savings in construction costs due to reducing uncertainty and the operational benefits of geotechnical systems obtained by probabilistic engineering approaches (Olaya et al., 2024).

Conclusion

The study findings showed that probabilistic design approaches contributed to the improvement of reliability, safety and performance of foundations and structures in the face of uncertainty in geotechnical conditions. The results showed that the uncertainties in soil properties, loading conditions and environmental factors had significant impacts on the stability of the foundations and behavior of the structure. The use of probabilistic frameworks was more accurate and realistic because it included the statistical variability, reliability analysis and uncertainty quantification in the engineering decision-making.

The mean values were high for Structural Safety and Stability (M = 4.21), Probabilistic Design Methods (M = 4.18), and Reliability Based Design (M = 4.12), indicating a high level of agreement among the respondents about the effectiveness of probabilistic methods in geotechnical engineering.

Further, correlation and regression analysis showed significant positive relationships between probabilistic design methods and reliability-based analysis, and structural performance. According to regression results, the reliability based design had the highest coefficient of β = 0.42 and significant p-value = 0.000 indicating that reliability based design contributed to the structural safety most. The study finally concluded that the use of probabilistic engineering methods in the optimization of foundations, reduction of structural risks and sustainable development of infrastructure under uncertain subsurface conditions was advantageous.

Recommendations

The study proposed using probabilistic design methods in the normal engineering process to enhance the reliability and safety of structures, for the benefit of geotechnical engineers and infrastructure planners. Reliability-based analysis, Monte Carlo simulation and uncertainty quantification methods should be more widely employed in the foundation design and geotechnical investigation stages of engineering works. Specialist training courses with an engineering background on the subject of probabilistic geotechnical engineering, statistical analysis, and risk-based infrastructure design, should also be offered by professional engineering institutions and universities to build up the technical skills of engineers and researchers.

Future Directions

Further studies are needed on how to combine the use of artificial intelligence, machine learning, and big data analytics in probabilistic geotechnical engineering frameworks for better predictive accuracy and computational efficiency. For complex geotechnical structures, such as foundations for offshore structures, buildings that are resistant to earthquakes, underground tunnels and high-rise structures, researchers should investigate the use of hybrid reliability models. The impact of climate change, groundwater variability, and environmental uncertainty on foundation performance and infrastructure resilience should also be explored in future studies.

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