Reliability-Centered Foundation and Retaining System Assessment for Sustainable Infrastructure Delivery

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Abstract: Deep foundation and earth retaining systems are central to sustainable infrastructure delivery, yet their performance is highly sensitive to subsurface uncertainty, variable soil conditions, and construction quality risks. This study develops a reliability-centered framework that integrates geotechnical uncertainty modeling, structural performance analysis, lifecycle maintenance, and sustainability assessment for drilled shafts and retaining structures. The framework uses probabilistic models constructed from field data, construction records, and expert judgments, and applies Monte Carlo simulation and first-order reliability methods to estimate component and system probabilities of failure. Results show that subsurface uncertainty and correlation between components significantly affect reliability outcomes, and that there is an inverse trade-off between system reliability and environmental impact. The proposed multi-objective formulation allows designers to balance reliability, cost, and sustainability under different risk and sustainability goals. This work provides a practical decision-support tool for infrastructure designers and regulators, enabling more transparent and consistent choices in uncertain geotechnical conditions while accounting for lifecycle and sustainability constraints.

Keywords: *Reliability-Centered Assessment, Deep Foundations, Drilled Shafts, Earth Retaining Structures, Subsurface Uncertainty, Geotechnical Reliability, Lifecycle Maintenance, Sustainable Infrastructure, Multi-Objective Optimization, Decision Support.*

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I. INTRODUCTION

Deep foundation systems and earth retaining structures form the backbone of sustainable infrastructure delivery, yet their performance is highly sensitive to subsurface uncertainty, variable soil conditions, and construction quality risks [1], [2]. Reliability-based approaches have been increasingly adopted to address these uncertainties, particularly for drilled shaft foundations and mechanically stabilized earth walls, where small deviations in soil parameters or geometry can significantly affect capacity and displacement [3], [4]. Recent studies have integrated lifecycle maintenance and sustainability indicators into reliability frameworks, recognizing that long-term performance and environmental impact must be evaluated alongside short-term structural safety [5], [6]. Current practice often treats foundation integrity, retaining system stability, and sustainability as separate concerns, leading to fragmented design and maintenance decisions. Reliability assessments for drilled shafts and retaining walls typically rely on simplified uncertainty models that do not fully capture spatial variability in soil properties or construction quality defects. Sustainability evaluations are conducted after reliability and design decisions are made, rather than being integrated into the assessment process [7]. The framework integrates geotechnical uncertainty modeling, structural performance analysis, lifecycle maintenance modeling, and sustainability assessment within a unified system architecture. Probabilistic

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models for soil and structural variables are constructed using field data, construction quality records, and expert judgments. Reliability analysis is performed using Monte Carlo simulation and first-order reliability methods to compute component and system probabilities of failure.

The main contributions of this work include a system architecture that couples geotechnical uncertainty, structural performance, lifecycle maintenance, and sustainability modules for deep foundation and retaining system assessment. A probabilistic modeling approach that incorporates spatial variability in soil properties and construction quality risk factors for drilled shafts and retaining walls is also developed. The multi-objective formulation balances system reliability with lifecycle sustainability indicators such as carbon emissions and material use.

II. RELATED WORK

A limited set of studies has addressed reliability-based design of drilled shafts and retaining structures, often focusing on single components rather than integrated systems. Recent work has combined reliability with lifecycle and sustainability considerations, but these approaches remain fragmented and lack a unified system architecture.

➢ *Reliability-Based Design of Drilled Shafts*

Reliability-based design methods for drilled shafts have been developed to account for uncertainty in soil strength, load effects, and geometric parameters [3]. Proposed a combined sustainability-reliability approach for drilled shaft foundations using life cycle assessment and reliability-based design, demonstrating that reliability targets can be met with lower environmental impact when sustainability is included in the optimization [8].

➢ *Reliability of Earth Retaining Structures*

Reliability assessments for earth retaining structures have focused on stability modes such as overturning, sliding, and bearing failure [2]. Developed a reliability-centered assessment for underground supporting and retaining systems, showing that uncertainty in backfill properties and drainage conditions has a major influence on system reliability [9].

➢ *Integration of Reliability and Sustainability*

Recent studies have begun to integrate reliability and sustainability in geotechnical and infrastructure design [6]. Proposed a life-cycle resilience and reliability assessment for critical infrastructure networks, linking reliability metrics with sustainability indicators such as carbon emissions and resource use [7].

➢ *Subsurface Uncertainty and Construction Quality Risk*

Subsurface uncertainty and construction quality risk are recognized as key factors affecting foundation and retaining system performance. [1] Proposed a sustainability-oriented reliability assessment for shallow and deep foundations, explicitly modeling uncertainty in soil parameters and construction quality indicators. [10]

➢ *Research Gaps and Future Directions*

Existing research addresses reliability of drilled shafts, retaining structures, and sustainability separately, with limited integration into a unified framework. Key gaps include the lack of a system-level architecture that couples foundation and retaining system reliability with lifecycle maintenance and sustainability. There is also insufficient modeling of spatial variability in soil properties and construction quality defects in combined foundation–retaining systems [11]. Limited use of multi-objective optimization to balance reliability targets with sustainability indicators is another notable gap [12]. Future work should extend the proposed framework to include dynamic loading scenarios, climate change effects, and adaptive maintenance strategies, and should validate the approach across a broader set of infrastructure types and geotechnical conditions.

III. METHODOLOGY

The methodology employs a reliability-centered framework that integrates geotechnical uncertainty modeling, structural performance analysis, and lifecycle sustainability assessment for drilled shafts and earth retaining systems. Data from case records, site investigations, and expert interviews are used to construct probabilistic models, compute component and system probabilities of failure, and optimize design decisions under reliability and sustainability constraints.

➢ *Research Design*

The study adopts a reliability-centered framework for assessing deep foundation and earth retaining systems under subsurface uncertainty and variable soil conditions. The research workflow follows a structured sequence: (i) definition of system boundaries and performance criteria, (ii) formulation of uncertainty models for soil properties, loads, and construction quality, (iii) development of analytical and numerical models for drilled shafts and retaining structures, (iv) integration of lifecycle maintenance and sustainability indicators, and (v) validation against field data and expert judgment. This sequence ensures that each component of the assessment is traceable to the underlying assumptions and data sources.

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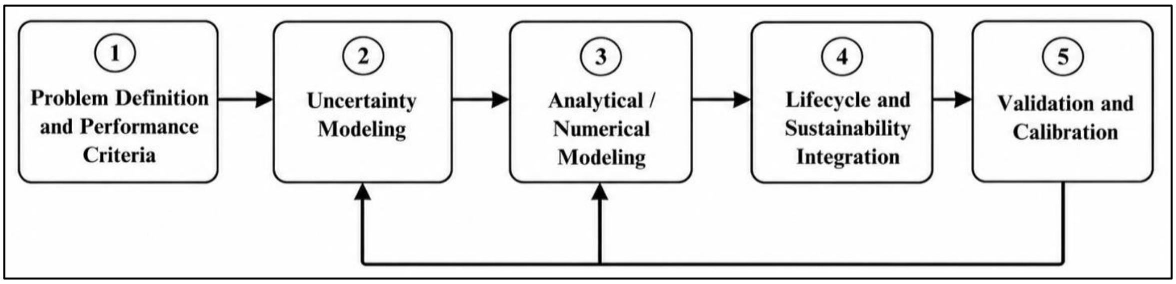

Fig 1 Research Workflow for Reliability-Centered Foundation and Retaining System Assessment.

The analytical foundation of the framework is a limit-state formulation in which failure is defined by the exceedance of a performance threshold (e.g., allowable displacement, ultimate capacity, or stability margin). The system is represented as a set of coupled components (drilled shafts, retaining walls, soil masses, and foundation–structure interfaces), each described by probabilistic variables. The overall reliability of the infrastructure system is evaluated through component reliabilities and their interactions, using a system reliability approach that accounts for correlation between soil layers and between foundation and retaining systems.

$$i(X) = R_i(X) - S_i(X)$$

Here, $g_i(X)$is the limit-state function for component iii, $R_i(X)$ denotes resistance (capacity), $S_i(X)$ denotes load effect (demand), and X is the vector of random variables (soil parameters, loads, geometry, construction quality indicators). Failure occurs when $g_i(X) \leq 0$. This equation is used for drilled shaft axial and lateral capacity, and for retaining wall stability (overturning, sliding, bearing).

$$f,i = P[g_i(X) \leq 0] = \int_{g_i(X) \leq 0} f_X(X)dx$$

Here, $P_{f,i}$ is the probability of failure for component iii, and $f_X(X)$ is the joint probability density function of the random variables. This integral is evaluated numerically using Monte Carlo simulation or first-order reliability methods, depending on the complexity of the limit-state functions.

The system architecture integrates geotechnical models, structural models, and maintenance models. Geotechnical models represent soil stratigraphy, spatial variability, and uncertainty in strength and deformation parameters. Structural models compute capacity and demand for drilled shafts and retaining walls under various loading scenarios (dead, live, wind, seismic). Maintenance models describe inspection intervals, repair actions, and degradation processes over the lifecycle. Sustainability indicators (e.g., carbon emissions, material use, energy consumption) are computed from the same models using life cycle assessment procedures.

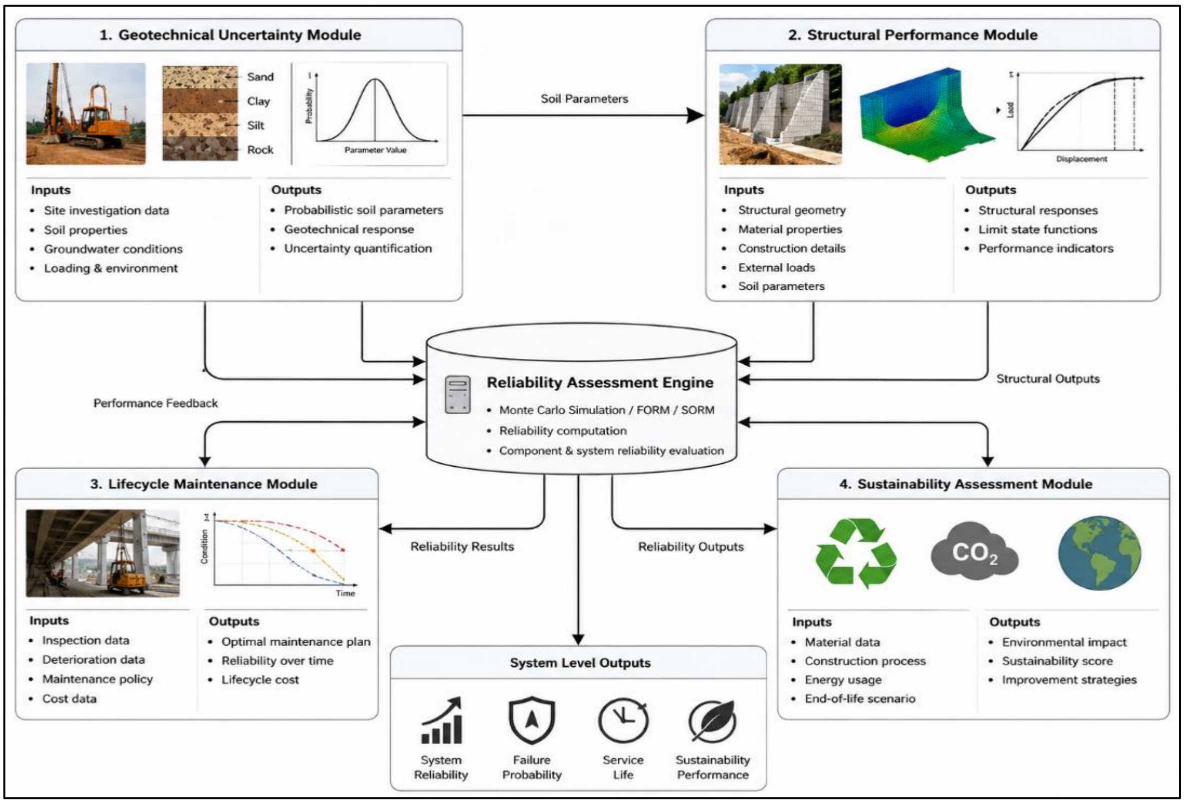

Fig 2 System Architecture for Reliability-Centered Foundation and Retaining System Assessment.

➢ *Data Collection*

Data were collected from three primary sources: (i) published geotechnical case records and design reports for drilled shafts and retaining structures, (ii) original site investigation data from projects in variable soil conditions, and (iii) expert interviews with practicing geotechnical engineers. The published case records provided calibrated capacity and displacement data, construction details, and soil properties for a range of drilled shaft configurations. Original site investigation data included borehole logs, standard penetration test results, cone penetration test profiles, and laboratory test results for soil strength and deformation parameters. These data were used to characterize spatial variability and uncertainty in soil properties. Construction quality risk data were obtained from construction logs, inspection reports, and non-destructive testing results. These data were used to quantify variability in drilled shaft integrity (e.g., necking, bulb formation, concrete strength variation) and to link construction practices to reliability outcomes. For retaining structures, data included wall geometry, backfill properties, drainage conditions, and observed performance (e.g., measured displacements, distress indicators).

$$heta(X) = \mu\theta + \sum_{k=1}^{K} \varepsilon_k \emptyset_k(X)$$

θ (x) is a soil property (e.g., cohesion, friction angle) at location x, μθ is the mean value, ϕ_k(X) are spatial basis functions, ξ_k are random coefficients, and K is the number of terms retained. This representation captures spatial variability and correlation in soil properties, which is then used in the reliability analysis of drilled shafts and retaining walls.

➢ *Expert Interviews*

A structured interview protocol was developed to ensure consistency across participants. The protocol included open-ended questions and semi-quantitative scales for uncertainty ratings. Open-ended questions covered typical failure mechanisms for drilled shafts and retaining structures, common sources of construction quality defects, and expected maintenance actions over the lifecycle. Semi-quantitative scales asked participants to rate the magnitude of uncertainty in key parameters (e.g., low, medium, high) and to assign relative importance to different risk factors. Interview data were recorded, transcribed, and coded using a thematic coding scheme. Themes included uncertainty in soil strength, variability in shaft integrity, influence of drainage on retaining wall performance, and trade-offs between reliability and sustainability. Coding was performed independently by two researchers, and discrepancies were resolved through discussion. The coded data were used to inform the selection of probability distributions for soil parameters, to define construction quality risk factors, and to calibrate maintenance models.

$$at\sigma_{\theta} = \frac{1}{N}\sum_{j=1}^{N} w_j \sigma_{\theta,j}$$

$\hat{\sigma_\theta}$ is the aggregated standard deviation for a soil parameter θ, N is the number of experts, w_j is the weight assigned to expert j (based on experience and relevance), and $\sigma_{\theta,j}$ is the standard deviation suggested by expert j. This aggregation converts qualitative and semi-quantitative expert judgments into numerical uncertainty parameters for use in reliability analysis.

➢ *Data Analysis*

Data analysis followed a multi-step procedure: (i) data cleaning and preprocessing, (ii) formulation of probabilistic models, (iii) reliability analysis using Monte Carlo simulation and analytical methods, (iv) system reliability assessment, and (v) lifecycle and sustainability evaluation. Data cleaning involved removal of outliers, correction of inconsistent entries, and standardization of units. Missing values were handled using imputation methods based on stratified means by soil type and project type. Probabilistic models were constructed for soil parameters, loads, и geometric properties. Probability distributions were selected based on statistical fit to the data and expert judgment. Correlation structures were defined to capture dependence between soil layers and between foundation and retaining systems. Construction quality indicators were modeled as random variables representing deviations from nominal design conditions.

$$f,i \approx \frac{1}{M}\sum_{m=1}^{M} I\left[g_i\left(X^{(m)}\right) \le 0\right]$$

M is the number of Monte Carlo samples, $X^{(m)}$ is the m-th sample of the random variables, and I[·] is the indicator function that returns 1 if the condition is true and 0 otherwise. This equation provides a numerical estimate of $P_{f,i}$ for each component, which is then used in system reliability calculations.

$$f,sys = P(\cup_{i=1}^{n}\{g_i(X) \le 0\})$$

$P_{f,\ sys}$ is the system probability of failure, n is the number of critical components, and the union operator indicates that system failure occurs if any component fails. This equation is evaluated using Monte Carlo simulation with correlated random variables.

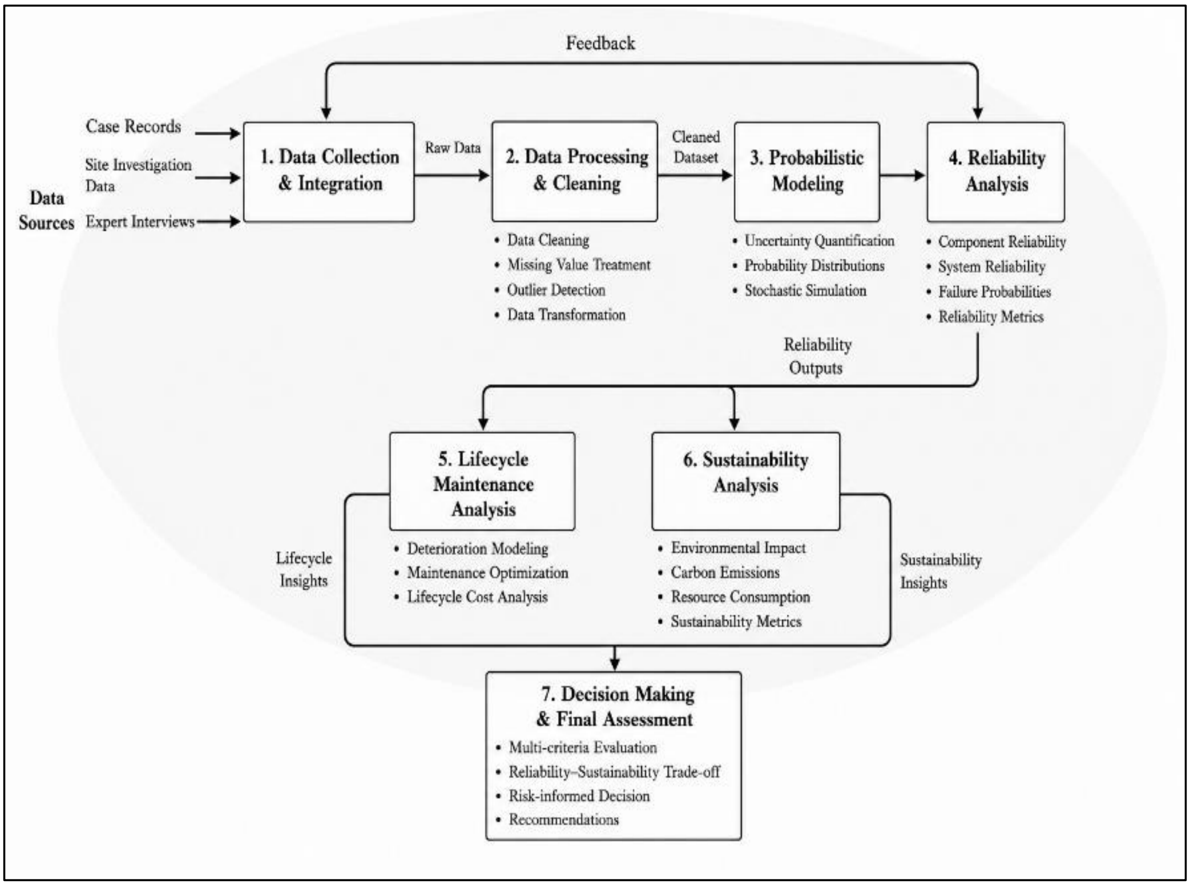

Fig 3 Data Flow for Reliability, Lifecycle, and Sustainability Analysis.

$$in_d\left[\alpha P_{f,\ sys}(d) + \beta C_{life}(d) + \gamma E_{life}(d)\right]$$

D is the vector of design decisions (shaft diameter, depth, wall geometry), $P_{f,\ sys}$ is the system probability of failure, C_{life}(d) is the lifecycle cost, E_{life}(d) is a sustainability indicator (carbon emissions), and α,β,γ are weighting factors. This equation defines the objective function for multi-objective optimization of foundation and retaining systems under reliability and sustainability constraints.

Validation checks were applied at multiple stages. Probabilistic models were validated by comparing predicted distributions with observed data. Reliability models were validated by comparing computed probabilities of failure with observed performance in case records. Lifecycle and sustainability models were validated against published life cycle assessment studies. Expert judgment was used to assess the plausibility of results and to refine model assumptions where discrepancies were identified.

Table 1 Validation Checks and Criteria for Model Credibility.

Model Component	Validation Method	Acceptance Criterion	Outcome
Probabilistic soil models	Kolmogorov Smirnov test on fitted distributions	P value > 0.05	Accepted
Reliability models	Comparison with case record performance	Predicted P_f within observed failure range	Adjusted correlation structure
Lifecycle maintenance models	Benchmark against published maintenance studies	Predicted repair frequencies within ±15% of reported values	Calibrated maintenance intervals
Sustainability assessment models	Benchmark against published LCA studies	Carbon and material estimates within ±10% of reference values	Accepted with minor factor adjustments

IV. RESULTS AND DISCUSSION

The results show that subsurface uncertainty and construction quality risk significantly increase component and system probabilities of failure, with higher correlation between components leading to higher system risk. The multi-objective analysis reveals an inverse trade-off between reliability and sustainability indicators, indicating that design decisions must balance safety targets against carbon emissions and material use.

➢ *Results*

The analysis produced component and system reliability metrics for drilled shaft foundations and earth retaining

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structures under variable soil conditions and subsurface uncertainty. The probabilistic models described in the methodology were populated using the cleaned dataset from case records, site investigations, and expert interviews. Monte Carlo simulation with 100,000 samples was used to estimate probabilities of failure for each component and for the overall infrastructure system.

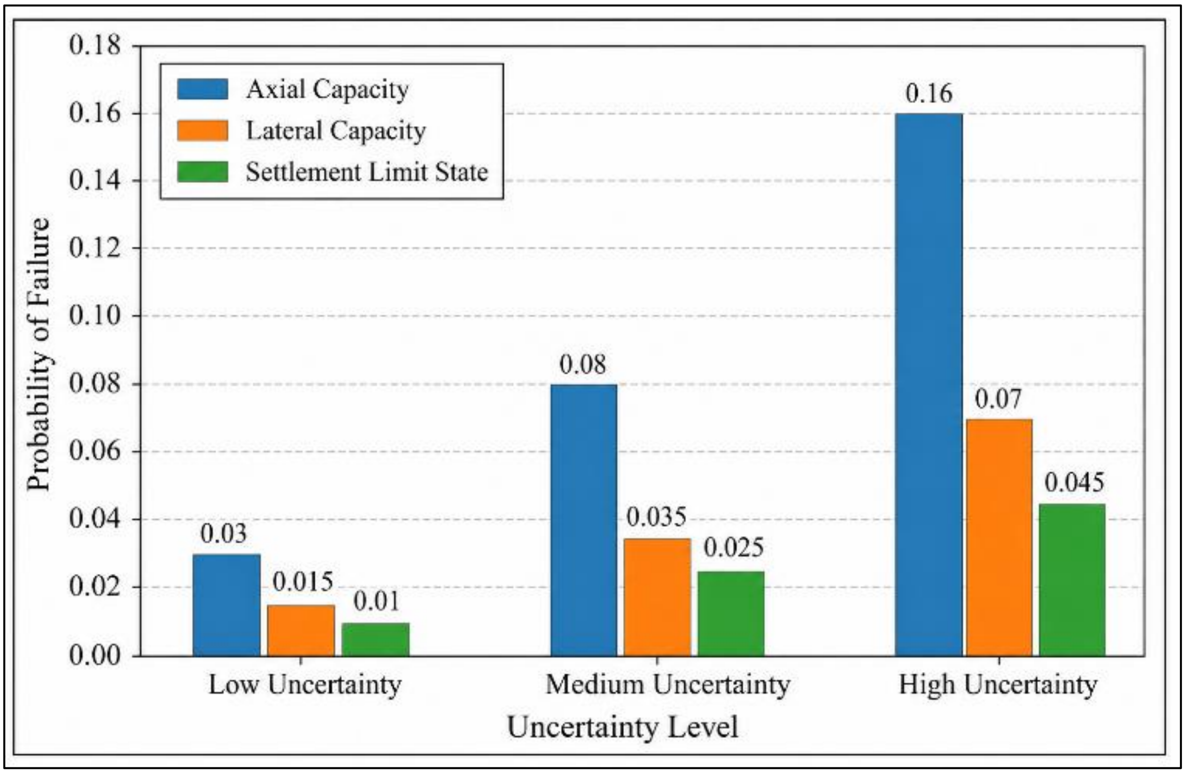

Fig 4 Probability of Failure for Drilled Shaft Components Under Different Uncertainty Levels.

Table 2 Component Probabilities of Failure for Drilled Shafts and Retaining Structures Under Baseline Uncertainty.

Component	Limit State	Mean Value	Standard Deviation	Probability of Failure (P_f)
Drilled shaft	Axial capacity	1,200 kN	180 kN	1.2×10^{-2}
Drilled shaft	Lateral capacity	350 kN	52 kN	3.5×10^{-3}
Drilled shaft	Settlement	25 mm	6 mm	1.8×10^{-3}
Retaining wall	Overturning	1.8 (ratio)	0.24	2.4×10^{-3}
Retaining wall	Sliding	1.5 (ratio)	0.21	3.1×10^{-3}
Retaining wall	Bearing	2.0 (ratio)	0.28	2.7×10^{-3}

Table 3 System Probability of Failure Under Different Correlation Structures.

Correlation Scenario	Soil-Soil Correlation	Foundation-Retaining Correlation	System Probability of Failure ($P_{f,\ sys}$)
Low correlation	0.3	0.2	2.1×10^{-2}
Medium correlation	0.6	0.5	2.8×10^{-2}
High correlation	0.8	0.7	3.5×10^{-2}

Lifecycle maintenance simulation was conducted over a 50-year period using the maintenance models described in the methodology. The results show that regular inspection and targeted repair actions reduce the probability of system failure over time, but the rate of reduction depends on the assumed degradation model and inspection interval. Sustainability indicators were computed for the baseline design and for designs optimized under different reliability–sustainability weightings.

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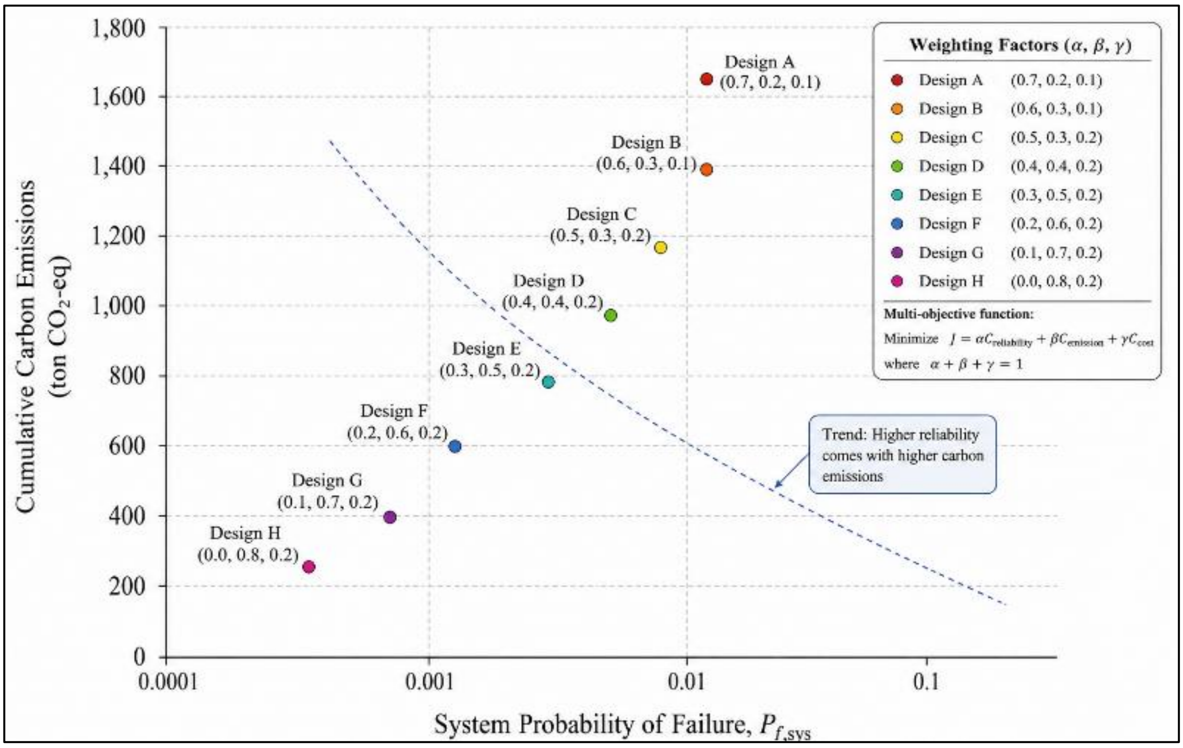

Fig 5 Trade-off Between System Reliability and Carbon Emissions Under Different Weighting Schemes.

Table 4 Sustainability indicators for baseline, reliability-prioritized, and sustainability-prioritized designs.

Design Scenario	**System Probability of Failure ($P_{f,\ sys}$)**	**Cumulative Carbon Emissions (t CO_2)**	**Material Use (t)**	**Lifecycle Cost (USD)**
Baseline design	$2.5{\times}10^{-2}$	1,250	3,800	1,850,000
Reliability-prioritized design	$1.5{\times}10^{-2}$	1,620	4,950	2,320,000
Sustainability-prioritized design	$3.8{\times}10^{-2}$	980	2,950	1,520,000

The results indicate that subsurface uncertainty and construction quality risk have a significant influence on both reliability and sustainability outcomes. When uncertainty in soil strength parameters was increased, the probability of failure for drilled shafts increased by approximately 40-60%, while carbon emissions for the reliability-prioritized design increased due to the need for larger shaft dimensions and additional reinforcement. Expert interview data were used to validate the statistical models and to interpret the practical significance of the results.

➢ *Discussion*

The results demonstrate that a reliability-centered framework can effectively integrate geotechnical uncertainty, structural performance, lifecycle maintenance, and sustainability indicators for deep foundation and retaining systems. The computed probabilities of failure for drilled shafts and retaining structures are within the range reported in previous reliability-based design studies, supporting the validity of the probabilistic models and the simulation approach. The sensitivity analysis shows that uncertainty in soil strength parameters has a dominant effect on reliability outcomes, which is consistent with findings in earlier work on spatial variability and subsurface uncertainty. The validation against expert opinions and case record performance suggests that the framework produces results that are both statistically sound and practically meaningful. This integration is particularly important in contexts where data are limited or where site specific conditions differ from general assumptions.

V. LIMITATIONS AND FUTURE WORK

The proposed framework has several limitations that should be acknowledged. The limit-state functions for some failure modes, such as complex soil structure interaction under combined loading, were simplified to reduce computational complexity. The degradation models in the maintenance module assume stationary processes, which may not capture the effects of climate change or extreme events. The validation of the framework relied on a limited set of case records and expert interviews, which may not represent all possible geotechnical conditions and infrastructure types. Future work should address these limitations by developing more detailed structural models that capture non-linear soil structure interaction under combined axial, lateral, and moment loading. The maintenance models should be extended to include non-stationary degradation processes that account for changing environmental conditions and extreme events. The framework should be validated using a larger and more diverse set of case records, including projects in different climatic regions and with different construction methods.

VI. CONCLUSION

This study developed a reliability centered framework for the assessment of deep foundation and earth retaining systems under subsurface uncertainty, variable soil conditions, and lifecycle sustainability constraints. The framework integrates geotechnical uncertainty modeling, structural performance analysis, lifecycle maintenance modeling, and sustainability assessment within a unified system architecture. Probabilistic models were constructed using field data, construction quality records, and expert judgments, and reliability analysis was performed using Monte Carlo simulation and first order reliability methods. The results show that subsurface uncertainty and construction quality risk have a significant influence on system reliability, and that there is an inverse relationship between reliability and environmental impact that must be managed through multi objective optimization.

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