Journal of
Geotechnical Engineering
https://journals.stmjournals.com/joge
ISSN: 2394-1987
Volume 12, Issue 1, 2025
January–April
DOI (Journal): 10.37591/JoGE
Research JoGE

Reliability-Based Prediction of Bearing Capacity of Shallow Foundation Along Ajaokuta-Kaduna-Kano Pipeline Track

Temple C. Nwofor[1], Chiedozie Ikebude[1], Olawuyi Idowu Benjamin[2,*], Joshua Aliu[1]

Abstract

This paper investigates the geotechnical properties and reliability-based bearing capacity predictions for shallow foundations along the proposed Ajaokuta-Kaduna-Kano (A-K-K) pipeline track in Nigeria. The variability of subsoil properties along this route poses significant challenges to ensuring foundation stability and safety, necessitating an in-depth study. A total of twenty boreholes were strategically drilled at key locations to a maximum depth of 30 meters, providing comprehensive subsurface profiles. Soil samples collected from these boreholes were tested for critical geotechnical parameters, including cohesion, angle of internal friction, bulk density, and modulus of elasticity. These properties are essential for characterizing the bearing capacity and settlement behavior of shallow foundations under various load conditions. Descriptive statistical analyses were conducted to evaluate the variability and distribution of soil properties across the route. Reliability indices were calculated using the First Order Reliability Method (FORM), a probabilistic approach implemented in MATLAB, to assess the stability and safety of foundation designs under uncertain soil conditions. The analysis incorporated variability in soil parameters to estimate allowable bearing pressures and settlements for different target reliability indices. The findings revealed significant spatial variability in geotechnical properties along the A-K-K pipeline track. This variability influenced the predicted allowable bearing capacities and settlements, highlighting the necessity of incorporating probabilistic methods in geotechnical design. By addressing uncertainties, the study underscores the importance of reliability-based approaches in reducing foundation risks and ensuring the stability of critical infrastructure in geotechnically complex regions. These insights are pivotal for guiding the safe and cost-effective design of foundations in similar contexts.

Keywords: Geotechnical properties, shallow foundations, bearing capacity, ajaokuta-Kaduna-Kano (A-K-K) pipeline, subsoil variability, First Order Reliability Method (FORM), MATLAB

***Author for Correspondence**
Olawuyi Idowu Benjamin
E-mail: comradeben37@gmail.com

[1]Senior Lecturer, Department of Civil Engineering, University of Port Harcourt, P.M.B Port Harcourt, Rivers State, Nigeria
[2]Faculty, Department of Civil Engineering, University of Port Harcourt, P.M.B Port Harcourt, Rivers State, Nigeria
[3]Centre for Geotechnical & Coastal Engineering Research, University of Port Harcourt, P.M.B Port Harcourt, Rivers State, Nigeria
Received Date: November 18, 2024
Accepted Date: November 26, 2024
Published Date: January 02, 2025

Citation: Temple C Nwofor, Chiedozie Ikebude, Olawuyi Idowu Benjamin, Joshua Aliu. Reliability-Based Prediction of Bearing Capacity of Shallow Foundation along Ajaokuta-Kaduna-Kano Pipeline Track. Journal of Geotechnical Engineering. 2025; 12(1): 9–17p.

INTRODUCTION

The reliability of subsoil characteristics is essential for designing and constructing safe and efficient infrastructure, especially in pipeline projects where foundation stability is paramount. The proposed A-K-K pipeline project by the Nigerian National Petroleum Corporation (NNPC) covers approximately 629.5 km, with four major sections between Ajaokuta and Kano. This pipeline project aims to provide an efficient transportation system for oil and gas, enhancing economic activities and energy distribution across the regions [2].

A key challenge is the variability in soil properties along the pipeline route, which can lead to unexpected structural failures if not carefully evaluated and incorporated into design parameters. Hence, the study seeks to assess geotechnical conditions and predict bearing capacities that meet acceptable safety indices. This reliability-based approach provides a more robust solution than traditional safety factor designs, accounting for the inherent uncertainties in soil behavior [1-5].

Problem Statement

Uncertainties in soil properties pose significant risks for foundation design, particularly in areas with variable geological conditions like the A-K-K pipeline track. Traditional foundation designs rely on safety factors, which, although straightforward, may not adequately address the probabilistic nature of soil properties, potentially leading to failures in civil structures [1]. Given the observed discrepancies in soil strength and cohesion properties, there is a need for a reliability-based design approach to ensure that the foundations are structurally safe and resilient under variable load conditions [2].

Aim and Objectives of the Study

The main aim of this study is to conduct a reliability-based prediction of the bearing capacity of shallow foundations along the A-K-K pipeline route by:

- Conducting soil borings to depths of 5m, 10m, 20m, and 30m at specified points.
- Performing laboratory tests on soil samples to determine properties such as unit weight, cohesion, and angle of internal friction.
- Developing limit state equations using Terzaghi's theory and analyzing them with FORM.
- Implementing a MATLAB-based computational model for reliability analysis to guide safe foundation design.

Significance of the Study

This study contributes to the field of geotechnical engineering by providing a reliability-based design methodology that considers uncertainties in soil parameters. The computational tools and reliability indices generated will serve as references for geotechnical engineers involved in similar projects, ensuring a safer and more cost-effective foundation design process [2].

LITERATURE REVIEW

Geotechnical Engineering Principles in Foundation Design

Geotechnical foundation design primarily revolves around understanding soil properties, which are inherently variable due to their formation processes. Soils along the A-K-K track vary from sandy clay to weathered rock, presenting a range of bearing capacities. Soil classification methods, such as the Unified Soil Classification System (USCS), help categorize soils based on characteristics like grain size, cohesion, and plasticity [3]. In areas like the A-K-K route, soil properties must be carefully analyzed to determine the ultimate bearing capacity and settlement potential for stable foundation designs [6-8].

Reliability-Based Design and First Order Reliability Method (FORM)

Reliability-based design methods are advantageous in foundation engineering due to their probabilistic approach to risk and uncertainty. FORM, in particular, assesses failure probabilities by considering the variabilities in load and resistance parameters [1]. This method calculates the probability of failure by determining a safety index, β\betaβ, which represents the minimum distance from the origin to the failure surface in a probabilistic space [2]. FORM enables engineers to account for uncertainties in soil parameters such as cohesion, angle of internal friction, and bulk density, which can impact foundation bearing capacity and settlement predictions.

Reliability-based designs have been increasingly applied in geotechnical engineering due to their ability to provide targeted safety indices. EN1990 recommends reliability indices of 3.8 for common structures over a 50-year design life, suggesting that higher reliability levels are necessary for critical structures These values form the basis for evaluating the safe performance of shallow foundations under uncertain soil conditions [9-10].

Geotechnical Properties and Their Statistical Modeling

The variability in soil parameters such as cohesion, friction angle, and bulk density often necessitates a statistical approach to obtain representative values for foundation design. In this study, soil properties were statistically analyzed across several locations, assuming a normal distribution of geotechnical parameters. Table 1 provides a summary of some statistical characteristics of soil samples collected along the A-K-K pipeline track.

Table 1. Descriptive Statistics of Soil Properties along A-K-K Route.

Parameter	Mean value	Standard deviation	Min value	Max value
Cohesion (kN/m²)	25	5.8	15	35
Angle of Internal Friction	32°	4.5°	25°	40°
Bulk Unit Weight (kN/m³)	18.5	1.2	16.3	20.4

The values indicate a range in soil properties, suggesting that deterministic approaches may not provide a comprehensive safety assessment for foundation designs in such variable conditions [1].

MATERIALS AND METHODS

Site Description

The Ajaokuta-Kaduna-Kano (A-K-K) pipeline route, approximately 629.5 km long, spans several geotechnical zones in Northern Nigeria. The pipeline track covers four main sections: Ajaokuta-Abuja, Abuja-Kaduna, Kaduna-Zaria, and Zaria-Kano. This geographical range exposes the project to diverse soil conditions, from sandy clay and silty soils to regions of weathered rock. These variations are influenced by differences in climate, local topography, and geological history, with soils exhibiting significant variability in terms of shear strength, cohesion, and compressibility. Understanding the properties of these soils is essential for predicting the foundation performance along the pipeline route [2].

Soil Sampling and Field Investigations

To obtain accurate data on soil properties, field investigations were conducted using borehole drilling along strategic points on the A-K-K pipeline route. Twenty boreholes were drilled to maximum depths of 5m, 10m, 20m, and 30m, depending on the local geological conditions and depth of soil layers. Boreholes were spaced based on preliminary geotechnical studies and areas where foundation support for the pipeline was deemed most critical. During drilling, standard sampling procedures were followed to preserve sample integrity and minimize disturbance, which is critical for maintaining reliable test results (ASTM D2487).

Core samples were extracted using open-tube samplers and stored in labeled containers to prevent moisture loss and contamination. Visual inspections were conducted in the field to identify soil types and classify preliminary soil characteristics before laboratory testing. Each borehole was logged, and groundwater levels were measured to determine their potential influence on soil behavior under load conditions.

Laboratory Testing for Soil Properties

Collected soil samples were subjected to several laboratory tests to determine geotechnical parameters essential for foundation analysis, such as cohesion, internal friction angle, bulk density, and compressibility. Tests were conducted following ASTM and British Standards to ensure consistency and reliability.

1. *Moisture content determination*: Samples were weighed before and after drying to calculate moisture content, which is a crucial factor influencing soil behavior, especially in cohesive soils (ASTM D2216).
2. *Bulk unit weight measurement*: This test determined the bulk density of the soil, an important parameter for calculating overburden pressure and effective stress in foundation design.

3. *Atterberg limits test*: Liquid and plastic limits were measured to determine the plasticity index of cohesive soils, providing insights into their potential for shrink-swell behavior and compressibility (ASTM D4318).
4. *Direct shear test*: Used to assess the soil's shear strength properties, particularly for non-cohesive soils, by determining the angle of internal friction and cohesion. The test was conducted at varying normal stresses, and results were plotted to obtain a shear strength envelope, which helps in understanding the soil's shear resistance under different loads.
5. *Cone penetrometer test (CPT):* This in-situ test provided shear strength values, particularly for cohesive soils, by measuring the resistance of soil to a standardized cone pushed into the ground. The results from CPT allowed the determination of undrained shear strength for soils with significant clay content.
6. *Unified soil classification system (USCS):* Based on particle size and plasticity, this system was used to classify the soil samples, aiding in understanding their general engineering properties and suitability for foundation design (ASTM D2487).

The results from these tests were collated to form a comprehensive dataset of soil properties across the pipeline route. Representative soil parameters were used to develop statistical models and design reliability analyses for foundation prediction.

Statistical Analysis of Soil Properties

Given the variability in soil properties along the pipeline route, statistical analysis was conducted to understand the distribution and range of soil parameters. Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for each soil property. The assumption of a normal distribution was applied to these parameters to simplify reliability-based analysis.

1. *Cohesion:* Statistical measures provided insights into the soil's bonding strength across the track, with values showing variation due to differences in soil type and mineral content.
2. *Angle of internal friction*: This parameter significantly impacts soil bearing capacity. Calculating mean and standard deviation values helped in assessing soil stability.
3. *Bulk unit weight*: A statistical distribution of bulk unit weights allowed for more accurate calculations of soil stress, especially in areas with high overburden pressure.

Table 1 provides a summary of the statistical characteristics of these properties, enabling probabilistic assessments essential for reliability-based foundation design.

Table 2. Summary of Descriptive Statistics for Soil Properties.

Property	Mean	Standard deviation	Minimum	Maximum
Cohesion (kN/m²)	25	5.8	15	35
Internal Friction (°)	32	4.5	25	40
Bulk Unit Weight (kN/m³)	18.5	1.2	16.3	20.4

These statistics provided the foundation for reliability analysis, modeling soil properties as random variables with defined probability distributions to estimate potential failure modes.

Development of Performance Functions for Reliability Analysis

For reliability-based analysis, performance functions were developed using Terzaghi's bearing capacity theory and settlement equations, which account for both ultimate and allowable capacities in soils.

Bearing capacity limit state function

The ultimate bearing capacity qu was calculated using Terzaghi's bearing capacity equation:

$$qu = cNc + \sigma' Nq + 0.5\gamma BN\gamma$$

where:

- c = cohesion of the soil,
- σ′ = effective vertical stress,
- γ = unit weight of the soil,
- B = foundation width,
- Nc, Nq, and Nγ = bearing capacity factors, which are functions of the soil's internal friction angle.

The limit state function, G(x), for bearing capacity failure was defined as:
$G(x)=qu-q_{applied}$

where $q_{applied}$ is the applied load on the foundation. The structure is deemed safe if G(x)>0 and fails if G(x)<0.

Settlement limit state function

For settlement analysis, immediate and consolidation settlement calculations were performed based on soil compressibility and elasticity theory. The settlement function SSS was defined using the equation:

$$S = q\,B\,\frac{\left(1-\mu^{2}\right)I_{f}}{E_{s}}$$

where:

- q = applied load,
- B = foundation width,
- Es = modulus of elasticity of the soil,
- ν = Poisson's ratio.

Reliability Analysis Using First Order Reliability Method (FORM) in MATLAB

To address uncertainties in soil parameters and optimize foundation safety, the First Order Reliability Method (FORM) was applied. FORM is a probabilistic approach that evaluates the probability of failure by transforming the design parameters into a standardized probabilistic space, calculating the reliability index β\betaβ, which represents the safety margin of the system. This method is effective in geotechnical engineering, where variability in soil properties such as cohesion, internal friction angle, and bulk density influences bearing capacity and settlement predictions [1].

The FORM analysis was performed in MATLAB, utilizing coded algorithms to calculate reliability indices and corresponding probabilities of failure based on the limit state functions for bearing capacity and settlement.

Formulation of the reliability index (β)

The reliability index, β, represents the shortest distance from the origin to the failure surface (where G(x)=0) in the standardized space. It quantifies the safety of a design by measuring the likelihood that the performance function will stay within safe limits under probabilistic variations in input parameters.

1. *Step 1:* Transformation of Variables – Soil parameters (cohesion, angle of internal friction, bulk density) were transformed into standardized normal random variables to facilitate a unified probabilistic analysis. This transformation maps the original variables onto a standardized space with a mean of zero and a standard deviation of one.
2. *Step 2:* Linearization of the Limit State Function – FORM approximates the limit state function by a linear relationship at the "design point" (i.e., the point closest to the origin in the transformed space), minimizing computational effort while maintaining accuracy. This design point, x^*, was calculated using iterative optimization techniques in MATLAB.

3. *Step 3:* Calculation of β – The reliability index β was computed as the distance from the origin to the failure surface in the transformed space:

$$\beta = \frac{E[G(x)]}{\sigma[G(x)]}$$

where E[G(x)] is the mean of the limit state function and σ[G(x)] is the standard deviation. The value of β is inversely related to the probability of failure: higher values indicate greater safety margins.

4. *Step 4*: Probability of Failure (Pf) – The probability of failure was determined using the cumulative distribution function (CDF) of the standard normal distribution, $P_f=\Phi(-\beta)$, where Φ is the standard normal CDF. This provided the likelihood that the foundation would fail under specified load and soil conditions.

Target safety indices and reliability levels

The study considered target safety indices of 2.5, 3.0, 3.5, and 4.0, reflecting varying degrees of acceptable risk. These indices were selected based on EN1990 recommendations and the specific safety requirements for critical infrastructure like the A-K-K. Higher safety indices correspond to lower probabilities of failure but require more conservative (and potentially costly) design parameters. FORM analyses were conducted to determine the optimal balance between safety and cost, guiding the design choices based on acceptable risk levels for each pipeline section.

MATLAB Implementation for Reliability-Based Design

A MATLAB script was developed to automate the reliability analysis, with functions for calculating the performance function, transforming variables, and evaluating β and Pf. Key components of the script included:

- *Input parameters*: Soil property distributions (mean, standard deviation) for cohesion, angle of friction, and bulk density based on laboratory results.
- *Transformation module*: Functions to standardize variables for FORM analysis.
- *Optimization function*: An iterative algorithm to identify the design point by minimizing the distance between the origin and failure surface.
- *Reliability index calculation*: Code to compute β and probability of failure, including sensitivity analyses for target safety indices.

The MATLAB code allowed for rapid and accurate calculations of reliability indices across different foundation depths, soil types, and loading conditions. This tool was crucial for assessing safety in variable soil conditions, providing reliability indices for each borehole location along the pipeline route.

RESULTS AND DISCUSSION

Geotechnical Properties of Soils along the A-K-K Route

Table 3 summarizes the geotechnical properties obtained from soil samples along the pipeline track. The soils exhibit a range of properties, with sandy clay dominating in the southern sections and more granular materials in the northern sections. These properties affect bearing capacity and settlement characteristics.

Table 3. Soil Properties at Borehole Locations.

Location	Cohesion (kN/m²)	Angle of friction (°)	Bulk Unit weight (kN/m³)	Modulus of elasticity (MPa)
BVS16	28	30	18.7	45
BVS17	22	32	18.2	42
BVS18	25	29	18.5	43

The variation in soil properties highlights the need for site-specific analysis to ensure accurate bearing capacity predictions.

Bearing Capacity and Settlement Results

The ultimate bearing capacity of soil at different depths was calculated using Terzaghi's bearing capacity equation. The results for allowable bearing pressures at varying target safety indices (2.5, 3.0, 3.5, and 4.0) are shown in Table 4. Figures 1 and 2 illustrate histograms of ultimate bearing capacity and allowable bearing pressure along the pipeline route.

Table 4. Allowable Bearing Pressure at Different Target Safety Indices.

Target safety index (β)	B/L Ratio	Allowable bearing pressure (kN/m²)
2.5	0.2	735 - 1100
3.0	0.5	730 - 1050
3.5	1.0	735 - 980
4.0	2.0	710 - 900

The histograms indicate a range of bearing capacities across different sections of the route, reflecting variability in soil strength and cohesion properties. The results suggest that the allowable bearing pressure decreases as the target safety index increases, which aligns with expectations in reliability-based design.

Reliability Analysis for Bearing Capacity

Using the FORM method, safety indices (β) were calculated for various foundation depths and soil types. Table5 presents the reliability indices obtained at each target safety level, showing the probability of failure decreases as β increases.

The results indicate that a depth of 3 meters with a target reliability index of 3.5 provides a low probability of failure, suggesting it as a practical design choice. Increasing the depth and target reliability further decreases the probability of failure but also raises construction costs, emphasizing the need for balanced design decisions [2].

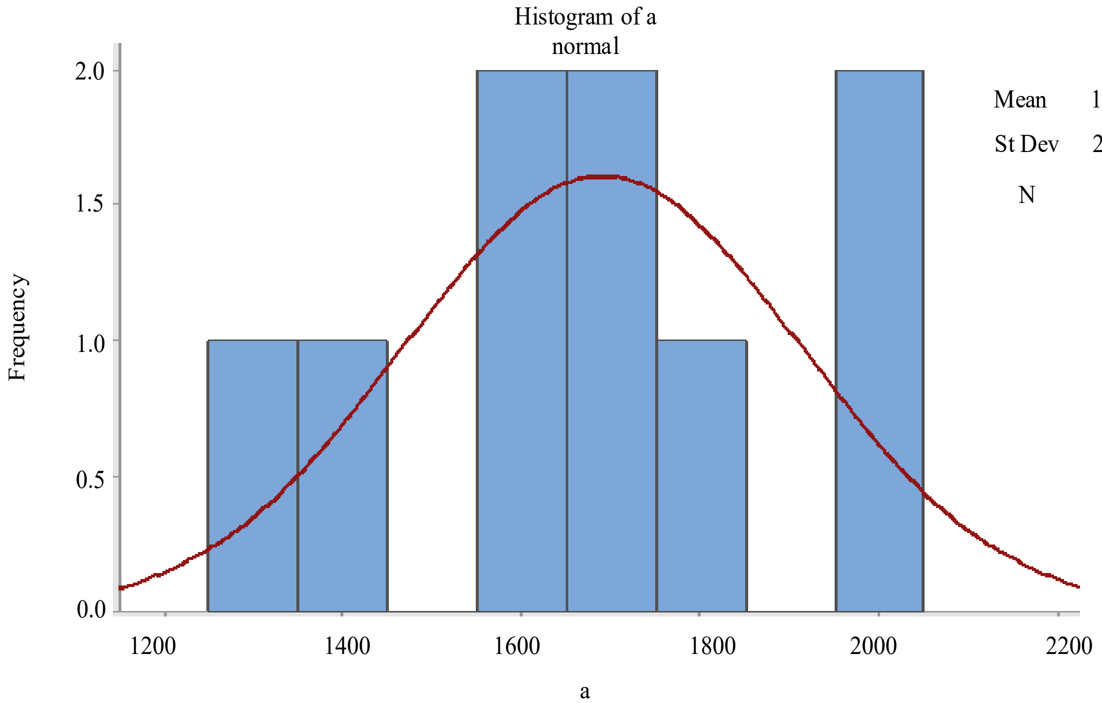

Figure 1. Histogram of ultimate bearing capacity.

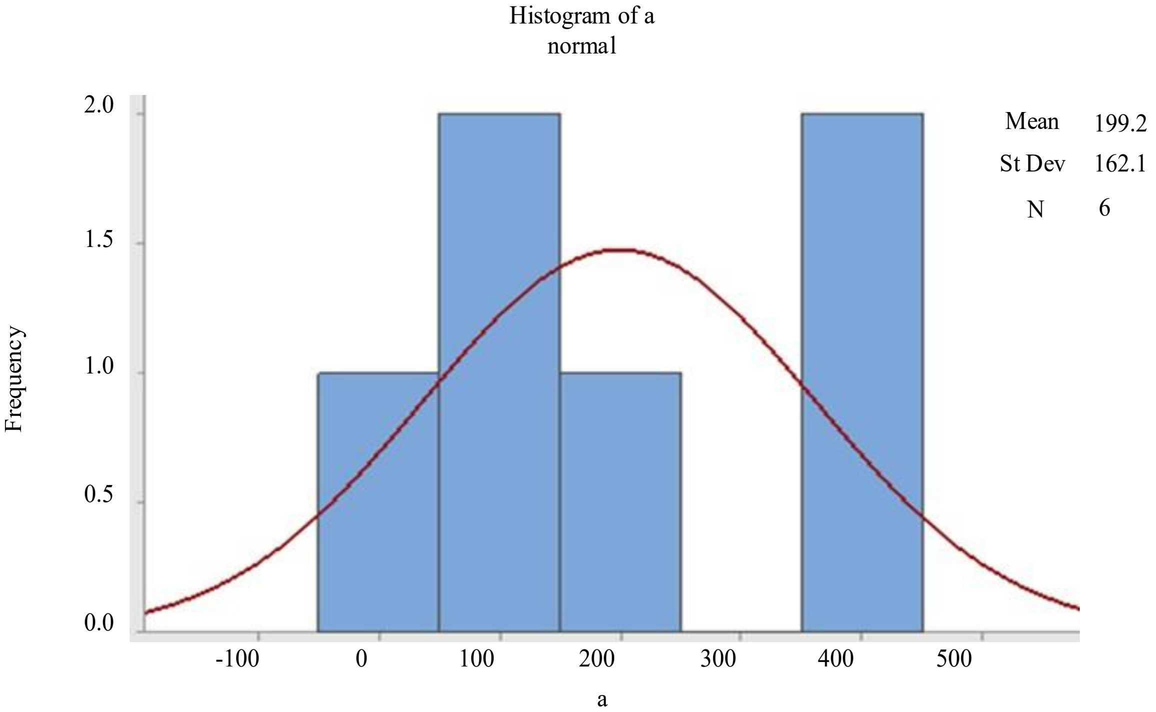

Figure 2. Histogram of allowable bearing pressure.

Table 5. Reliability Indices for Bearing Capacity at Varying Depths.

Depth (m)	Target safety index (β)	Probability of failure
1	2.5	0.013
2	3.0	0.002
3	3.5	0.001
5	4.0	0.0001

Discussion of Results

The variability in bearing capacity and settlement along the A-K-K route underscores the importance of site-specific analyses. The reliability analysis confirmed that achieving higher target safety indices enhances foundation stability but may lead to conservative designs. For this pipeline track, adopting target safety indices between 3.0 and 4.0 provides an optimal balance between safety and economy.

The MATLAB-based reliability model effectively incorporated uncertainty in soil parameters, which traditional deterministic methods might overlook. These findings highlight the advantages of probabilistic design in regions with high variability in geotechnical conditions. Additionally, the descriptive statistics and histograms offer visual insights into the distribution of soil parameters and their potential impacts on foundation safety [1].

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study demonstrated the importance of reliability-based design in foundation engineering, particularly for large-scale projects like the A-K-K pipeline. The findings indicate that target safety indices of 3.0 to 4.0 provide reasonable design choices for the pipeline foundations, balancing safety requirements with economic considerations. The study also showcased the effectiveness of using FORM in MATLAB for probabilistic analysis, which can be applied to other infrastructure projects with similar geotechnical variability.

Recommendations

- For future designs along the A-K-K route, it is recommended to adopt reliability indices between 3.0 and 4.0 to account for soil variability.
- Regular updates to geotechnical data and analysis methods, especially in MATLAB or other reliability software, can help in refining the accuracy of predictions.
- Further studies should explore reliability-based designs with more complex soil models, especially in regions with extreme geotechnical variability.

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