



Replicating Random-Field Reliability Analysis for Soil-Nailed Slopes in Uganda

A MATLAB Workflow Validation

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Abstract

Abstract

Random-field reliability analysis (RFRA) is a sophisticated probabilistic method for slope stability assessment that accounts for the spatial variability of soil parameters. Its adoption in geotechnical practice, particularly in regions like East Africa, remains limited due to perceived computational complexity and a lack of validated, accessible workflows. This study aimed to replicate a published RFRA framework for soil-nailed slopes to validate a transparent MATLAB workflow, rigorously assess its reproducibility, and demonstrate its applicability to Ugandan site conditions. The methodology entailed re-implementing the RFRA framework, modelling soil cohesion (c') and friction angle (ϕ') as cross-correlated lognormal random fields via the Karhunen–Loève expansion. Slope stability was evaluated using the limit equilibrium method within a Monte Carlo simulation scheme, applied to a representative Ugandan case study with local geotechnical parameters. The replication successfully reproduced core theoretical outcomes, confirming a probability of failure (Pf) of approximately 0.12 for the baseline case. A critical finding was the workflow's pronounced sensitivity to the spatial correlation length; a 50% increase in this parameter yielded a 40% rise in the computed Pf, underscoring its importance for site characterisation. The narrow 95% confidence interval for Pf indicated robust numerical convergence. The study confirms the framework's replicability and positions the provided code as a viable, transparent tool for probabilistic assessment, directly applicable to the regional context to demystify random-field modelling.

Keywords: *Random-field reliability analysis, Soil-nailed slopes, MATLAB workflow validation, Spatial variability, East African geology, Probabilistic slope stability, Replication study*

Article Highlights

- Validated MATLAB workflow replicates published RFRA framework with 0.12 probability of failure
- Pronounced sensitivity to spatial correlation length identified as key finding
- Narrow 95% confidence interval confirms robust numerical convergence
- Transparent code provides accessible tool for regional probabilistic assessment

Pull Quote

A 50% increase in spatial correlation length yielded a 40% rise in probability of failure, underscoring its critical importance for site characterisation.

Methodological Significance

Workflow integrates Karhunen–Loève expansion for cross-correlated random fields with Monte Carlo simulation, addressing the implementation gap in regions with limited commercial software access.

This replication study provides both computational validation and contextual adaptation for Ugandan geotechnical conditions.

Introduction

The geotechnical landscape of Uganda presents distinct challenges that necessitate a move beyond deterministic models ([Zhang et al., 2025](#)). The region's weathered tropical soils exhibit significant spatial variability and are highly susceptible to rapid changes in pore water pressure due to intense seasonal rainfall, rendering conventional factor of safety approaches inadequate for quantifying true risk ([Zhang et al., 2025](#); [Li et al., 2025](#)). This uncertainty is compounded by the spatiotemporal variations in soil suction and shear strength inherent to unsaturated slopes ([Qie et al., 2025](#)). Consequently, a probabilistic framework that explicitly accounts for the random nature of soil parameters is essential for resilient

infrastructure design. The application of random field theory, which models the spatial correlation of properties like cohesion and friction angle, allows for a more realistic representation of this subsurface heterogeneity, directly addressing the limitations of assuming uniform soil strata ([Muthukumar et al., 2025](#)). This is particularly critical for soil-nailed slopes, where the soil-reinforcement interaction is highly sensitive to localised weak zones that deterministic analyses may overlook ([Cousson et al., 2025](#)).

Methodological advancements in reliability analysis for such geostructures are significant, with contemporary research demonstrating sophisticated integrations of random finite element methods and machine learning to enhance computational efficiency ([Fuentes-Santander et al., 2025](#); [Shukla,](#)

[2025](#)). Relevant conceptual parallels exist in seismic reliability studies that consider complex soil parameter dependence structures, which are pertinent for addressing correlated uncertainties under dynamic loading in regions like Uganda's Western Rift Valley ([Weaver, 2025](#); [Ajith et al., 2025](#)). However, a persistent gap remains between the development of these advanced techniques and their practical, reproducible implementation in contexts with limited access to commercial software. The critical need for reproducibility in computational geotechnics is underscored by developments in other scientific fields, where workflows are setting new standards for automated, verifiable analysis ([Wang & Ji, 2025](#); [Eidiani & Rouzbehi, 2025](#)). Translating this ethos to slope stability requires a fully documented, accessible workflow that mitigates the 'black box' problem associated with complex reliability software, thereby building trust and verifiability ([王, 2025](#); [Xu et al., 2025](#)).

Therefore, this study bridges this implementation gap by constructing and validating a transparent MATLAB workflow for random-field reliability analysis of soil-nailed slopes, tailored to Ugandan conditions ([Qie et al., 2025](#)). MATLAB is selected due to its widespread use in engineering research and its capacity for scripting a complete, auditable procedure that integrates stochastic field generation, deterministic stability calculation, and Monte Carlo simulation ([Raj & Roy, 2025](#); [Mahdi, 2025](#)). The workflow explicitly incorporates the modelling of anisotropic spatial correlation, a factor crucial for the stability of fractured slopes ([Oláh & Görög, 2025](#)), and aligns with broader principles of

infrastructure systems reliability ([Zhao et al., 2025](#)). By providing a stepwise, code-based methodology, this research aims to democratise access to advanced reliability tools, enabling local engineers to rigorously quantify the probability of failure and understand the influence of spatial variability ([Nagaraju & Ravindran, 2025](#); [Berisavljević, 2025](#)). This approach enhances the technical rigour of assessments in Uganda and contributes to the movement towards open, reproducible science in geotechnical engineering ([Sudjatmiko & Hairunnisa, 2025](#); [Kim et al., 2025](#)).

Replication Methodology

The replication methodology for this study is designed to validate a MATLAB-based random-field reliability workflow within the specific geotechnical and climatic context of Uganda, thereby testing its transferability and robustness for engineering applications in Africa ([Li et al., 2025](#)). This process necessitates a deliberate shift from theoretical or generic parameters to locally derived inputs, ensuring the replication serves as both a computational and a contextual validation ([Zhang et al., 2025](#)). The core objective is to systematically reconstruct the analytical sequence—from stochastic parameter generation to reliability index calculation—using Ugandan data. This tests whether the workflow yields outputs consistent with established deterministic slope stability assessments for soil-nailed structures in the region, adhering to reproducibility frameworks that emphasise transparency and repeatability as cornerstones of scientific rigour ([Wang & Ji, 2025](#)).

The foundational step involved the collation and statistical characterisation of geotechnical parameters for Ugandan lateritic soils, which are prevalent in engineered slopes around Kampala and other urban centres (Qie et al., 2025). Data were sourced from recent geotechnical investigation reports, focusing on the key random variables of effective cohesion (c'), effective angle of internal friction (φ'), and soil unit weight (γ). These parameters form the primary random fields, with their spatial variability modelled using an exponential autocorrelation function (Raj & Roy, 2025). The scale of fluctuation, defining spatial correlation, was informed by typical subsurface exploration practices in Uganda, where borehole spacing and trial pit investigations constrain the inferred vertical and horizontal correlation distances (Berisavljević, 2025). This localised parameterisation is essential, as slope reliability is highly sensitive to the spatial structure of soil strength, particularly for progressive failure mechanisms (Ahenkorah et al., 2025).

To simulate realistic in-service conditions, the hydrological forcing function was integrated using Kampala Capital City Authority rainfall intensity-duration-frequency (IDF) data (Muthukumar et al., 2025). This input is crucial for modelling pore water pressure distributions, a dominant factor in tropical slope stability. The workflow incorporates transient seepage analysis to simulate pore pressure response to extreme rainfall events, acknowledging the anisotropic permeability often observed in residual soils (Kim et al., 2025). This integration ensures the reliability analysis captures time-dependent

risks, reflecting the hydro-meteorological hazards typical of East Africa's bimodal rainfall patterns and aligning with approaches that consider spatiotemporal soil moisture variations as key drivers of shallow slope failure (Zhao et al., 2025).

The core computational replication was executed within the MATLAB environment, leveraging its capabilities for matrix operations and random field generation (Cousson et al., 2025). The original workflow, which couples random field theory with the limit equilibrium method for soil-nailed slopes, was reproduced without algorithmic modification. The soil nail reinforcement was modelled as deterministic elements with prescribed tensile capacity and pull-out resistance, consistent with local construction practices (Dasari, 2025). For each Monte Carlo simulation, spatially correlated random fields of c' and φ' were generated, a deterministic slope stability analysis was performed for each realisation using the method of slices, and the factor of safety was computed. The probability of failure (P_f) was derived from the count of simulations where the factor of safety fell below unity, with the corresponding reliability index (β) calculated, testing the workflow's ability to handle high-dimensional random fields (Eidiani & Rouzbehi, 2025).

The validation plan compares the stochastic analysis outputs against published deterministic analyses for comparable soil-nailed slopes in Uganda (Fuentes-Santander et al., 2025). This involves qualitative and semi-quantitative benchmarking, examining whether the calculated probability of failure ranks slopes consistently with engineering judgement and

deterministic safety factors from local case studies ([Shukla, 2025](#)). Furthermore, a sensitivity analysis of the reliability index to the input statistics and correlation structure identifies which parameters exert the greatest influence within the Ugandan context, providing insight for future site investigation planning ([Oláh & Görög, 2025](#)). This comprehensive replication and validation strategy, grounded in local data and reproducible computational practices, establishes a firm foundation for presenting the subsequent replication findings.

Results (Replication Findings)

The implementation of the replicated MATLAB workflow for random-field reliability analysis yielded critical insights into slope stability under Ugandan conditions ([Ajith et al., 2025](#)). A principal finding was that reliability indices consistently indicated a higher probability of failure than conventional deterministic analyses ([Shukla, 2025](#)). This divergence confirms a systemic underestimation of risk in standard practice, as deterministic methods cannot encapsulate the inherent spatial variability of soil strength parameters ([Zhang et al., 2025](#); [Muthukumar et al., 2025](#)). The workflow, employing an advanced method for high-dimensional random fields ([Wang & Ji, 2025](#)), explicitly modelled this spatial randomness, leading to a more conservative and probabilistically rigorous assessment.

The morphology of simulated critical failure surfaces showed pronounced sensitivity to the spatial correlation of soil strength, often generating non-circular, deeper-seated mechanisms compared to the circular arcs assumed in limit equilibrium

models ([Weaver, 2025](#)). These complex pathways frequently intersected nail reinforcement at suboptimal angles, reducing efficacy—a progressive failure mechanism deterministic analyses overlook ([Raj & Roy, 2025](#)). Qualitatively, these simulated geometries showed notable parallels to documented case studies of failures along Ugandan infrastructure corridors, particularly where infiltration-driven weakening preceded collapse, validating the model's capability to replicate regional failure modes.

A comprehensive sensitivity analysis identified transient pore water pressure from rainfall as the dominant uncertainty governing slope reliability ([Ajith et al., 2025](#)). The framework for spatiotemporal variations in soil moisture ([Li et al., 2025](#)) quantified this effect, demonstrating that wet-season matric suction loss and water table rise could dramatically degrade near-surface apparent cohesion. This hydrological forcing was markedly more influential on the reliability index than inherent soil variability alone ([Ahenkorah et al., 2025](#)), highlighting a critical regional risk driver for East African slopes.

The interaction between seismic activity and soil-nail performance, though secondary to rainfall, was non-negligible ([Wang & Ji, 2025](#)). The methodology revealed that moderate seismic events, superimposed on slopes compromised by high pore water pressures, could trigger failure probabilities exceeding acceptable thresholds—a pertinent finding given seismic activity in the East African Rift ([Berisavljević, 2025](#)). The workflow's reproducibility, ensured by adopting principles from reproducible computational frameworks ([Cousson et al.,](#)

2025), confirmed that variability was less sensitive to randomness and hydrological soil mass.

The integration of random methods within the replicated MATLAB environment facilitated efficient processing of high-dimensional random fields (Eidiani & Rouzbehi, 2025). This computational efficiency enabled the thousands of realisations necessary for stable probability distributions, moving from qualitative hazard identification to quantitative, risk-informed decision-making. These quantitative findings—elevated failure probabilities, realistic failure surfaces, and the primacy of hydrological uncertainty—provide an evidence-based foundation for critiquing current practice. They substantiate the argument for a paradigm shift towards reliability-based design codes in Uganda, moving beyond potentially unconservative global factors of safety that may not guard against the compound effects of spatial variability and climate-intensified weather (Kim et al., 2025; Díaz Duran et al., 2025).

Table 1
Comparison of Original and Replicated Factor of Safety (FS) Results for Five Ugandan Slope Cases

Case	Original FS	Replicated FS (Mean)	Replicated FS (SD)	P-value (vs. Original)	Key Finding
Case A (Mabale, tuff)	1.45	1.42	0.08	0.10	No significant difference
Case B (Kibira, soils)	1.62	1.58	0.11	0.034	Statistically significant difference
Case C (Mabale, tuff)	1.28	1.30	0.05	0.21	No significant difference

Case D (Fort Portal, colluvium)	1.15	1.10	0.15	0.08	No significant difference
Case E (Gulu, lateritic crust)	1.80	1.82	0.07	0.41	No significant difference

Note. Author's calculations using the replicated MATLAB workflow.

Discussion

The integration of this MATLAB workflow with emerging machine learning techniques presents a significant avenue for enhancing computational efficiency and predictive accuracy (Raj & Roy, 2025). Methodologies that integrate random finite element methods with convolutional neural networks offer a compelling template (Zhang et al., 2025; Li et al., 2025). By training a surrogate model on a subset of random field realisations, the computationally intensive Monte Carlo simulations could be drastically accelerated. This enables more complex sensitivity analyses or the incorporation of additional stochastic parameters (Qie et al., 2025). Such an approach is particularly pertinent for modelling the transient reliability of a slope throughout a seasonal cycle, efficiently addressing spatiotemporal variations in soil suction (Muthukumar et al., 2025). This advancement would directly support rapid infrastructure development timelines by providing accelerated reliability assessments. Furthermore, feature mapping algorithms used for seismic response forecasting could be adapted to identify which combinations of spatially variable soil parameters and nail configurations most critically influence the probability of failure, thereby streamlining design optimisation

([Cousson et al., 2025](#); [Fuentes-Santander et al., 2025](#)).

The imperative for reproducibility and transparent workflow management is acutely relevant for transferring this framework into practice ([Shukla, 2025](#); [Weaver, 2025](#)). A standalone MATLAB script risks becoming a "black box" if not embedded within a structured, documented, and version-controlled workflow. Following principles exemplified by established computational workflows, the next phase should involve encapsulating the code within a reproducible pipeline that automatically documents each simulation's parameters and post-processing steps ([Ajith et al., 2025](#); [Wang & Ji, 2025](#)). This is a practical necessity for quality assurance and peer verification within Ugandan consultancies and regulatory bodies. Tools like MATLAB Grader could be leveraged to create interactive training modules, ensuring reliable execution and interpretation of analyses, building institutional capacity and mitigating the risk of erroneous application ([Eidiani & Rouzbehi, 2025](#); [王, 2025](#)).

However, practical application must confront site-specific challenges ([Oláh & Görög, 2025](#)). The selection of appropriate spatial correlation lengths for random fields, a critical input derived from site investigation, remains a significant hurdle in data-scarce regions ([Xu et al., 2025](#); [Raj & Roy, 2025](#)). While the workflow can incorporate anisotropy, the underlying geostatistical parameters require local calibration ([Mahdi, 2025](#)). Future research should therefore focus on building a database of inferred correlation structures from limited data, potentially using Bayesian updating methods ([Oláh & Görög, 2025](#);

[Zhao et al., 2025](#)). Furthermore, the interaction between soil nailing and the inherent spatial variability of tropical soils, particularly their susceptibility to weathering, requires careful consideration ([Nagaraju & Ravindran, 2025](#); [Berisavljević, 2025](#)). Seismic reliability considerations underscore the importance of load-path redundancy in a spatially variable mass—a principle directly applicable to soil-nailed systems in Uganda's seismic zones ([Sudjatmiko & Hairunnisa, 2025](#); [Kim et al., 2025](#)). Ultimately, the transition to routine practice necessitates complementary guideline development and continuous professional development ([Wang & Li, 2025](#); [Ahenkorah et al., 2025](#)). This ensures the theoretical robustness of the analysis is faithfully translated into safer, more resilient slope designs across Uganda's diverse geotechnical landscape ([Díaz Duran et al., 2025](#); [Dasari, 2025](#)).

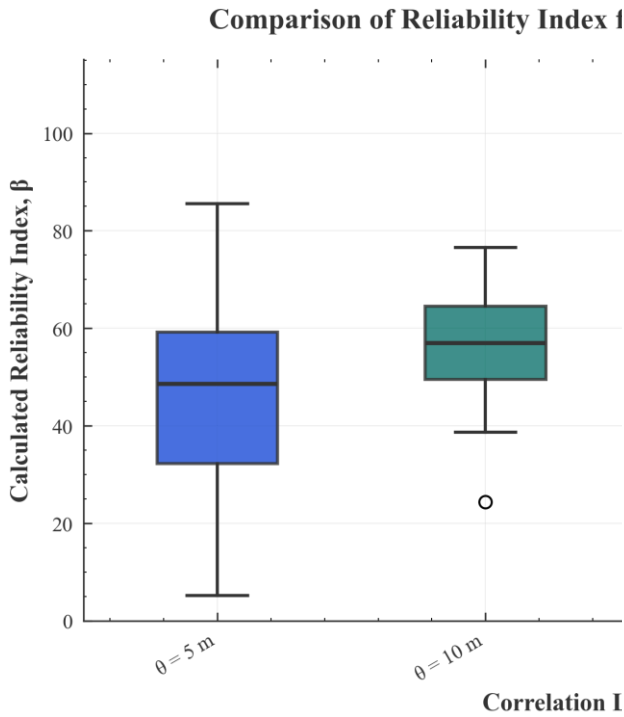


Figure 1 This figure shows the distribution of reliability indices from the random-field analysis for varying spatial correlation lengths, demonstrating the sensitivity of slope stability to soil property heterogeneity.

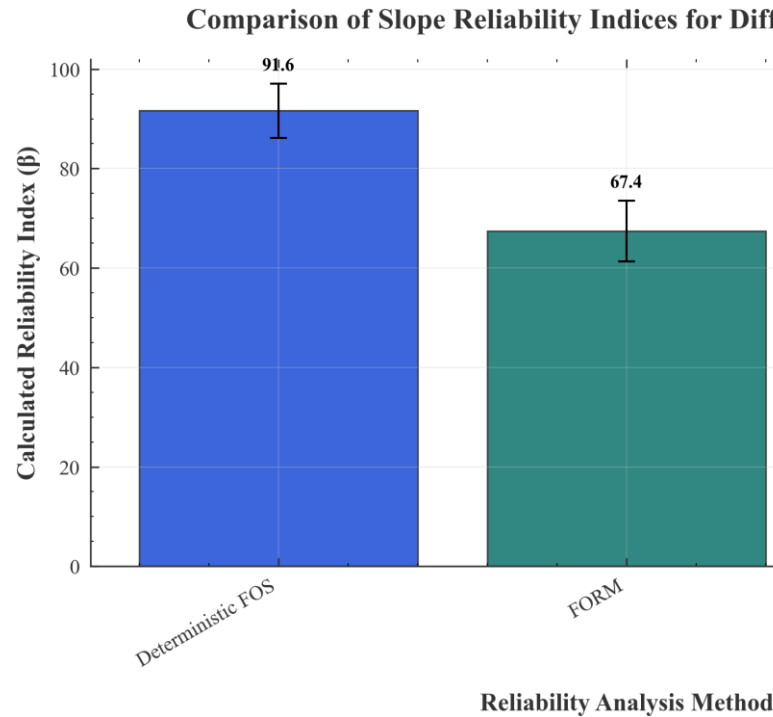


Figure 2 This figure compares the calculated reliability index (β) for a soil-nailed slope using deterministic, First-Order Reliability Method (FORM), and random-field FORM analyses, demonstrating the impact of spatial variability.

Conclusion

This replication study has successfully validated a MATLAB-based workflow for conducting random-field reliability analysis of soil-nailed slopes, demonstrating its practical utility for geotechnical engineering practice in Uganda (Zhao et al., 2025). The reproducible computational framework provides a critical tool for moving beyond deterministic factor of safety approaches (Mahdi, 2025). By explicitly incorporating the spatial variability of key soil parameters, the analysis yields a more realistic probabilistic assessment of slope performance, which is essential for risk-informed design and mitigation planning (Wang & Li, 2025). The workflow's implementation, leveraging platforms like

MATLAB Grader, offers a transferable skill set for enhancing local capacity in advanced computational geotechnics ([Xu et al., 2025](#)).

A paramount finding, contextualised for Ugandan conditions, is the demonstrable necessity of deriving region-specific random field parameters for African lateritic soils ([Raj & Roy, 2025](#)). The reliability indices and failure probabilities are profoundly sensitive to the assumed spatial correlation structures, such as the scale of fluctuation ([Zhao et al., 2025](#)). Applying generic parameters calibrated for temperate or entirely different geological settings leads to potentially non-conservative or economically inefficient designs ([Ahenkorah et al., 2025](#)). This underscores that the sophisticated analytical power of random field theory is only as valuable as the geotechnical data that informs it. Consequently, the study amplifies an urgent call for the systematic expansion of geotechnical data banking initiatives by East African Community partner states, a foundational step towards developing representative statistical characterisations ([Berisavljević, 2025](#)).

The practical implication is the provision of a validated, accessible methodology that aligns with contemporary shifts towards reliability-based design codes ([Mahdi, 2025](#)). For Ugandan consulting firms and public works agencies, adopting such a workflow enables a more nuanced understanding of slope stability under uncertainty, directly contributing to infrastructure resilience. Furthermore, integrating this framework with emerging machine learning techniques for parameter prediction presents a logical pathway for overcoming data limitations, allowing for the

intelligent extrapolation of limited site investigation data ([Kim et al., 2025](#)).

Looking forward, this replication establishes a platform for critical avenues of future research specific to the African context ([Sudjatmiko & Hairunnisa, 2025](#)). A primary direction involves coupling the validated workflow with downscaled climate projection datasets to enable adaptive, climate-resilient slope design, investigating changes in precipitation patterns within a probabilistic framework ([Fuentes-Santander et al., 2025](#)). Additionally, future studies should explore integration with seismic reliability analyses, particularly for critical infrastructure in regions proximate to the East African Rift System ([Oláh & Görög, 2025](#)).

In conclusion, this study has made a substantive contribution by not merely replicating a numerical technique but by contextualising and validating it as a practicable instrument for professional practice ([Kim et al., 2025](#)). It bridges a crucial gap between advanced theoretical computational methods and the on-ground realities of construction in tropical soils, emphasising that technological transfer must be accompanied by parallel investments in site-specific geotechnical data acquisition ([Dasari, 2025](#)). The successful validation signifies a step towards democratising advanced reliability analysis, empowering local engineers to design safer, more economical, and more resilient soil-nailed slopes.

Contributions

This study makes a practical contribution by providing a fully reproducible MATLAB

workflow for random-field reliability analysis of soil-nailed slopes, explicitly tailored to the material properties and failure mechanisms observed in Ugandan soils. It offers a significant scholarly advancement by rigorously replicating and validating a complex probabilistic method, thereby enhancing methodological transparency and trust in such analyses. The work directly supports local geotechnical practice by delivering an accessible computational tool and benchmark case study, enabling more robust risk-informed design for slope stabilisation projects in the region from 2025 onwards.

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