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Optimizing Reliability Analysis of Unsaturated Slopes through Polynomial Chaos Expansion over the Crude Monte Carlo Simulations

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Extended Abstract

This research investigates Polynomial Chaos Expansion (PCE)-enhanced Monte Carlo Simulation (MCS) for probabilistic slope stability analysis in unsaturated soils, presenting a significant advancement over traditional methods. Slope stability in unsaturated soils is complex due to variable soil properties like matric suction, cohesion, friction angle, and unit weigh, that influence shear strength. The Limit Equilibrium Method (LEM), particularly its grid and radius method, is widely used but computationally intensive, especially for unsaturated slopes where fitting parameters of Soil-Water Characteristic Curve (SWCC) affect stability. This study utilizes UQlab [1], a MATLAB-based uncertainty quantification tool, to develop and implement PCE models [2] as a surrogate model within MCS to efficiently compute the probability of failure in unsaturated slopes. PCE approximates complex nonlinear systems with fewer model evaluations, making it ideal for probabilistic stability analysis with significant variability. By integrating PCE into MCS, a surrogate-based approach is developed that maintains accuracy while reducing computational load in estimating the critical factor of safety for the critical slip surface, compared to Crude MCS, which requires many simulations to achieve reliable results. An unsaturated shear strength model [3,4] is used to incorporate soil suction's effect on failure probability, a critical factor in slope stability. Input parameters such as SWCC fitting parameters, cohesion, friction angle, and unit weight are treated as random variables, offering a comprehensive analysis of slope behavior under unsaturated conditions. To optimize the PCE model, leave-one-out cross-validation (LOO-CV) is used, ensuring suitable polynomial degrees to minimize error and prevent overfitting. This validation method enhances the generalization ability of the PCE model, promoting accurate predictions across different input sets. Results show that the PCE-enhanced MCS approach closely approximates the reliability index found in Crude MCS but with substantially reduced computational cost. This efficiency is particularly advantageous for unsaturated soil slope stability, where capturing the lowest probability of slope failure requires numerous simulations. By reducing the number of LEM evaluations, particularly with the Morgenstern-Price method of slices, the PCE-enhanced approach offers a practical solution for geotechnical engineers to perform cost-effective probabilistic analyses. In summary, this study introduces a practical, efficient framework for slope reliability analysis in unsaturated soils, leveraging PCE-enhanced MCS to provide accurate, reliable results with lower computational demands. This method advances current slope stability practices and opens pathways for probabilistic approaches in geotechnical engineering designs, promoting safer and cost-effective infrastructure projects.

Keywords: Slope Stability Analysis; Surrogate Modelling; Monte Carlo Simulations; Unsaturated soil mechanics; Polynomial Chaos Expansion; Limit Equilibrium Method.

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