（ 続紙 1 ）

京都大学	博士（工学）	氏名	VARGAS TAPIA RUBEN RODRIGO
論文題目	Comprehensive Validation of Numerical Predictions for Liquefaction-Induced Lateral Spreading（液状化による地盤の側方流動に対する数値解析予測の包括的な妥当性確認）		

Soil liquefaction is a complex geotechnical phenomenon that occurs under cyclic loading, causing the soil to experience a sudden loss of strength and stiffness, resulting in significant damage to buildings, infrastructure, and other critical structures. Accurate modeling of this phenomenon is essential for predicting soil behavior during seismic events and formulating effective mitigation strategies. Although computational modeling of geomaterials has experienced significant advancements over the last decades, rigorous verification and validation (V&V) processes are essential to gain credibility, ensure the reliability, and facilitate their integration into standard design practices. Past V&V efforts have ranged from qualitative comparisons (between physical models and numerical models) to probabilistic approaches based on limited non-crosschecked experimental data. However, it has been observed that even when conducted under controlled laboratory conditions, "identical" physical models performed in different facilities can yield significant differences in results. This highlights the need to use cross-checked data to verify the accuracy of experimental data and allow a proper uncertainty quantification for a comprehensive validation of numerical models.

This study addresses the existing gaps by introducing a novel, fully probabilistic validation methodology based on state-of-the-art validation procedures, for numerical models that predict liquefaction. It uniquely incorporates cross-checked experimental data, enabling a more accurate representation of physical model variability. The study presents the details of the proposed methodology through an actual validation exercise to explore the capabilities of the "Strain Space Multiple Mechanism Model," focusing on the simulation of lateral spreading across various relative densities and peak ground acceleration values. Utilizing an extensive, internationally cross-checked database of centrifuge experiments, the research enables accurate characterization of mean trends and variability in physical models.

Chapter 1 introduces the study, outlining the background, challenges, and the need for a robust fully probabilistic validation methodology in the field of soil liquefaction. It defines the objectives, underscores the novelty of the study, and details the proposed methodology, highlighting its significance in advancing current practices.

Chapter 2 presents a thorough literature review, examining various aspects including liquefaction, lateral spreading, centrifuge modeling, effective stress models, state-of-the-art in validation standards, and current validation efforts. The chapter critically analyzes existing studies, pointing out their advancements and limitations.

京都大学	博士（工学）	氏名	VARGAS TAPIA RUBEN RODRIGO

Chapter 3 describes in detail the physical models used in the validation exercise. Including comprehensive descriptions of the specifications, testing processes, data processing techniques, and uncertainty quantification. The chapter emphasizes the importance of the development of high-quality physical models.

Chapter 4 elaborates on the element tests (Hollow Cylinder Cyclic Torsional Shear Tests) conducted to study the mechanical properties of the target soil, required for calibrating the numerical model. The chapter includes meticulous details about the testing specifications, procedures, data processing, and uncertainty quantification.

Chapter 5 describes in detail the process of numerical modeling, covering the element simulation process, model parameter estimations, uncertainty definition and propagation, and simulations to replicate the physical models. The chapter illustrates the numerical modeling process, describing the governing equations, constitutive models, and numerical techniques employed.

Chapter 6 presents the final step of the validation exercise, including a probabilistic assessment of the numerical model outcomes based on the physical model outcomes. The importance and significance of the proper definition of validation metrics is discussed in detail; in addition, an assessment through Type B Simulations is performed, demonstrating that most of the important characteristics of the soil behavior (acceleration, excess pore water pressure, and displacement) can be properly simulated for reliable and repeatable tests, even in drastic condition changes.

The final chapter summarizes the key findings of the study, underscoring the successful implementation of the proposed fully probabilistic validation methodology to validate complex numerical models for liquefaction prediction. It also outlines future research directions, suggesting ways to build upon this work for further advancements in the field.

Through the manuscript, it is shown that the proposed methodology allows a comprehensive evaluation of numerical model’s capabilities to simulate the liquefaction-induced lateral spreading phenomena; this enhances the model’s reliability and contributes to its integration into common geotechnical engineering design practices/standards. Furthermore, the methodology proposed on this study have important implications for the improvement of numerical models for predicting soil liquefaction, and it can be used as a basis for future research by applying the validation methodology to other models and datasets.

(続紙 ２)

氏　名	VARGAS TAPIA RUBEN RODRIGO

本論文は、地震時の地盤の液状化による側方流動を予測する数値解析手法の包括的な妥当性確認の方法を提案し、室内試験や遠心模型実験に適用したものである。ASME V&V に基づく数値解析手法の妥当性確認は近年地盤工学分野でも実施されているが、地盤の液状化による側方流動を対象とした検討はない。本論文は、室内試験や複数機関で実施した遠心模型実験を対象とし、不確実性の定量化に基づいて数値解析との比較を行っている点が包括的な検討となっており、新規性を評価できる。

対象とした現象は、傾斜した飽和砂地盤の地震時の液状化による側方流動であり、様々な地盤の相対密度と入力加速度が側方変位をはじめとする地盤の動的挙動に与える影響を検討している。数値解析手法として、ひずみ空間マルチメカニズムモデルを用いた既存の動的有効応力解析手法を用いた。地盤材料の室内試験として、中空ねじり試験を用いて様々な相対密度と繰返しせん断応力比における繰返しせん断特性を調べた。この特性を数値解析手法の材料パラメータ設定に用いている。遠心模型実験として、同一の実験条件を設定し、国際研究プロジェクトにおいて世界 10 機関で実施した一斉実験結果を用いた。これには出願者自身が京都大学で実施した実験結果も含まれている。これらの室内試験および遠心模型実験の代表的な結果に対して回帰モデルを設定し、そのパラメータを MCMC 法によって推定することで、平均値やばらつきを定量的に評価した。これらの不確実性を定量化した遠心模型実験結果と数値解析結果の比較を通じて数値解析手法の妥当性を検討した。その結果、地震後の地盤の側方変位について、加振の最大加速度＜0.25g かつ 50％＜地盤の相対密度＜85%の場合には実験値の 95%信頼区間に解析値が収まることを確認し、その妥当性を確認することができた。

以上のように、本論文は液状化による側方流動を予測する数値解析手法の包括的な妥当性確認の方法を提案し、その適用例を示したものである。この方法は不確実性を有する様々な地盤解析手法に適用可能なものであり、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和６年１月１９日、論文内容とそれに関連した事項について試問を行った結果、合格と認めた。