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DesignSafe use-case: Constitutive model parameter calibration and site response analysis using integrated SimCenter tools and DesignSafe infrastructure

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ABSTRACT

Liquefaction under cyclic loads can be predicted through advanced (liquefaction-capable) material constitutive models. However, such constitutive models require input parameters whose values are often unknown or imprecisely known, requiring calibration via lab/in-situ test data. In this use-case, we take advantage of recently developed SimCenter tools and DesignSafe infrastructure to address this problem. The proposed solution uses a Bayesian updating framework that integrates probabilistic calibration of the soil model and probabilistic prediction of lateral spreading due to seismic liquefaction. The framework consists of three main parts: (1) Parametric study based on global sensitivity analysis, (2) Bayesian calibration of the primary input parameters of the constitutive model, and (3) Forward uncertainty propagation through a computational model simulating the response of a soil column under earthquake loading. The SimCenter workflow implemented in quoFEM and SimCenter backend-applications is combined with DesignSafe infrastructure and Jupyter notebooks to provide a flexible analysis framework easily extended to other engineering problems.

Introduction

Earthquake-induced soil liquefaction can lead to unexpected casualties and property loss, and therefore, it is essential to predict its risk in advance. Soil behavior under cyclic loads can be simulated using liquefaction-capable constitutive models [1]. Among them, PM4Sand is a sand plasticity model capable of simulating liquefaction under a broad mix of conditions in the field, including a wide range of density, shear stress, confining stress, and drainage/loading conditions [2]. This model has been implemented in numerical analysis software, including the

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open-source computational framework OpenSees [3,4]. The flexibility of such a model is attained through a large number of parameters (most of which are typically set to their recommended default values) as well as a wide search space of the possible parameter combinations [5]. While in-situ or lab test results provide information for calibrating unknown parameters [6], some challenges remain in using deterministic calibration methods. For example, the large search space of input parameters and potential multimodality of the calibration objective function make the optimizer susceptible to fall in local optima. Further, soil properties often can only be measured indirectly and reveal high spatial variability, thus limiting the credibility of parameter values estimated from limited test data. Consequently, after identifying a combination of optimal parameter values, a significant amount of uncertainty remains in the estimated parameter values as well as in the response predicted by the model [7]. Therefore, there is a need for adopting probabilistic calibration methods and performing forward uncertainty propagation. For example, by introducing the Bayesian calibration approach, correlations and interactions between parameters as well as multimodality can be captured in terms of multiple near-optimal parameter combinations, i.e., posterior distribution or samples, and such probabilistic representation allows prediction of the uncertainty propagating to the liquefaction-induced lateral spreading at a site of interest [8,9,10]. Additionally, probability-based sensitivity analysis of input parameters allows to identify the importance of each parameter while taking inherent uncertainty into account [11,12].

Analysis Strategy

In this study, we propose a systemized approach for probabilistic liquefaction prediction updating that consists of three steps: (1) parametric study, (2) parameter calibration based on experimental data, and (3) response prediction. Each analysis step can be greatly accelerated using the research tool quoFEM developed by the NHERI SimCenter at UC Berkeley [13] and DesignSafe infrastructure. quoFEM is an open-source software application developed to assist researchers and practitioners in the field of natural hazard engineering. It allows users to link different simulation engines, including OpenSees and FEAP [14] and advanced uncertainty quantification (UQ) and optimization methods with a user interface. Each step of the framework introduces variance-based global sensitivity analysis, transitional Markov chain Monte Carlo-based Bayesian updating, and forward resampling algorithms, respectively, among other alternatives supported in quoFEM. In this use-case Cyclic Direct Simple Shear (CyDSS) test data of Ottawa F-65 sand from Morales et al. (2021) is utilized to calibrate the PM4Sand model to match the prediction of an experimental cyclic strength curve (i.e., the number of cycles to the onset of liquefaction given the cyclic shear stress ratio) from the model to that obtained from the tests [3,15]. This cyclic strength curve becomes the objective function used to calibrate the constitutive model parameters. After Bayesian calibration, the uncertainty in the estimated values of the primary input parameters are used as inputs to a 1D soil column model representing the behavior of a layered soil profile subject an earthquake ground motion record. The lateral displacements experience by the column is used as the response quantity of interest.

All three steps require multiple realizations suitable to HPC parallel simulations. This is particularly true for the selected propagation of uncertainty step (i.e. lateral spreading analysis) that requires the use of large simulation models. To mitigate this problem, all quoFEM functionality has been incorporated into the SimCenter backend-applications framework installed in the TACC Frontera supercomputer; which can be used as part of the NHERI-DesignSafe CI allocation. In this way, all analyses can be conducted on high-performance computers at DesignSafe-CI using the user interface or Jupyter Notebooks run in the DesignSafe Jupyter-Hub.

The results shown in this presentation demonstrate the potential of the framework linked with quoFEM and DesignSafe to perform calibration and uncertainty propagation using sophisticated simulation models that can be part of a performance-based design workflow.

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