On Validation of a Two-surface Plasticity Model for Soil Liquefaction Analysis

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Abstract Constitutive modeling of granular materials such as sands, non-plastic silts, and gravels has been significantly advanced in the past three decades. Several new constitutive models have been proposed and calibrated to simulate the results of various laboratory element tests. Due to this progress and owing to the surge of interest in geotechnical engineering community to use well-documented constitutive models in major geotechnical projects, a more thorough evaluation of these models is necessary. Performance of the current models should be particularly evaluated in the simulation of boundary value problems where stress/strain paths are much more complex than the element tests performed in laboratory. Such validation efforts will be an important step towards the use of these models in practice. This paper presents the results of an extensive validation study aimed at assessing the capabilities and limitations of a two-surface plasticity model for sands in two selected boundary value problems, i.e. lateral spreading of mildly sloping liquefiable grounds. The results of a large number of centrifuge tests conducted during the course of four consecutive international projects known as Liquefaction Experiments and Analysis Project (LEAP) are used in this validation study. The capabilities and limitations of the two-surface plasticity model, initially calibrated against element tests, will be carefully assessed by comparing the numerical simulations with the results of the centrifuge tests from recent LEAP projects.
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Keywords: Constitutive Modeling, Lateral Spreading, Liquefaction, Sand, Random Finite Element Analysis, Soil-Structure Interaction

1 Introduction

The unprecedented computational power available at relatively low cost, the emergence of highly sophisticated numerical modeling platforms that allow for dynamic analysis of nonlinear porous media, and the recent advances in constitutive modeling of soil and other geomaterials have presented a unique opportunity for adoption of advanced numerical modeling in geotechnical engineering. A major first step towards the wider acceptance and use of numerical modeling in geotechnical engineering design and analysis is the verification and validation of the various components of a numerical modeling platform. Validation of the constitutive models embedded/implemented in the numerical modeling software is certainly a key step towards achieving this goal.

The Liquefaction Experiments and Analysis Projects (LEAP) are a series of international research collaborations aiming to produce high quality experimental data to facilitate the validation of constitutive and numerical modeling techniques that are currently available for modeling the response of geo-structural systems that involve liquefiable soils. During the past 6 years, three LEAP projects (LEAP-GWU-2015, LEAP-UCD-2017, and LEAP-Asia-2019) have been completed. Each LEAP involved three major steps: a) element laboratory tests to characterize the stress-strain-strength behavior of the soil of choice for the LEAP projects (Ottawa F65 sand) in monotonic and cyclic loading conditions, b) centrifuge tests conducted at major centrifuge facilities around the world, and c) a calibration and prediction exercise where a large number of numerical modelers first calibrate the constitutive models of their choice against the results of the laboratory element tests and then predict the results of dynamic centrifuge tests.

The main theme of the first two LEAP was liquefaction-induced lateral spreading of mildly sloping ground. LEAP-GWU-2015 served as the first step to establish the international collaboration and to assess the opportunities and challenges encountered in such an undertaking.

In LEAP-GWU-2015, the numerical modelers were provided a number of monotonic and strain-controlled cyclic triaxial tests conducted at the George Washington University (Vasko, 2015) to calibrate their constitutive models and use the models for type-A simulation of five different centrifuge tests (Kutter et al., 2017). The results of the calibration and prediction exercise were discussed in the LEAP-GWU-2015 workshop in Washington DC (Manzari et al., 2017, Zeghal et al., 2017).

LEAP-UCD-2017 focused on the issues of repeatability and sensitivity of the centrifuge test results to variation of density and base motion intensity. This time, a larger set of element tests including stress-controlled cyclic triaxial tests were provided to the predictors for further calibration of their models. Nine centrifuge facilities conducted 24 centrifuge tests covering a wide range of densities and base motion intensities. Type-B and Type-C simulations of a select number of the 24 centrifuge tests were submitted by 11 different prediction teams from around the world. Moreover, the predictors investigated the sensitivity of their simulations to the changes in soil density and base motion intensity. The results of LEAP-UCD-2017 project including all the experimental data and the comparisons between the experiments and predictions have been archived for free public access (Kutter et al., 2020a&b, ElGhoraiby et al., 2018, Manzari et al., 2020a&b).

This paper presents a brief summary of the work on calibration and assessment of the performance of the critical state two-surface-plasticity model for sands (Manzari and Dafalias, 1997; Dafalias and Manzari, 2004) in simulation of the centrifuge tests conducted during LEAP-GWU-2015, LEAP-UCD-2017, and LEAP-Asia-2019.

2 Calibration of the Constitutive Model

To start the validation process, the critical state two-surface plasticity model (Dafalias and Manzari) was first calibrated to simulate the number of cycles required to reach initial liquefaction (excess pore water pressure of 95% and above) in cyclic strain-controlled tests conducted during LEAP-GWU-2015 project (Vasko, 2015). Figure 1 shows a comparison of the model simulation of the liquefaction strength curve against the experimental data. The calibrated model is then used to simulate the stress-controlled cyclic triaxial tests. Very good match was obtained at cyclic stress ratios (CSR) above 0.15 (i.e., the shear stress ratios intended to be developed in the centrifuge tests), however the model showed smaller number of cycles to reach liquefaction at smaller CSRs. Further details are discussed on these simulations elsewhere (ElGhoraiby and Manzari, 2020).

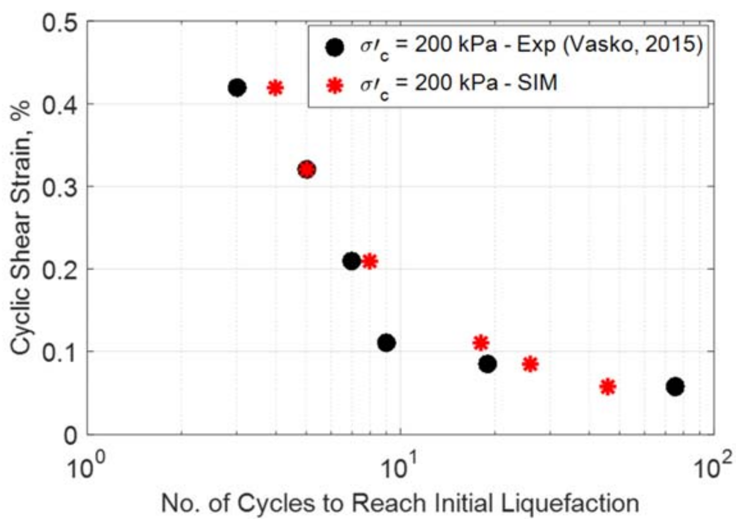

Fig. 1 Comparison of the observed and simulated liquefaction strength curves for undrained strain-controlled cyclic triaxial tests on Ottawa F65 sand with confining stress of 200 kPa.

3 Simulation of Lateral Spreading

Simulation of a boundary value problem for which reliable experimental data is available was the next step in the assessment of the model performance. During the LEAP-GWU-2015 and LEAP-UCD-2017 projects, a large number of centrifuge tests were conducted at the University of California, Davis, Rensselaer Polytechnic Institute (RPI), Cambridge University (UK), Kyoto University's Institute for Disaster Prevention (Japan), Zhejiang University (China), KAIST University (South Korea), Ehime University

(Japan), IFSTTAR (France) to simulate the lateral spreading of a mildly sloping ground (Figure 2). Each participating centrifuge facility attempted to prepare the soil specimen with a specified density and subjected the prepared specimen to a ramped sinusoidal base motion with the frequency of 1 Hz. The peak ground acceleration varied among different facilities but in many cases, the target peak acceleration 0.15g.

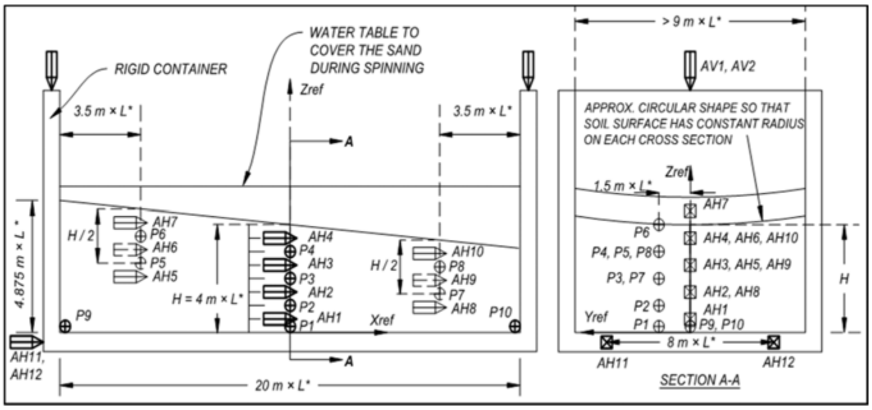

Figure 2: Schematics of the LEAP Lateral Spreading Centrifuge Experiment for shaking parallel to the axis of rotation

The experiments conducted at RPI showed remarkable consistency in terms of the achieved soil density and base motion intensity (Figure 3). Hence for the purpose of the model performance, the experiments conducted at RPI are selected.

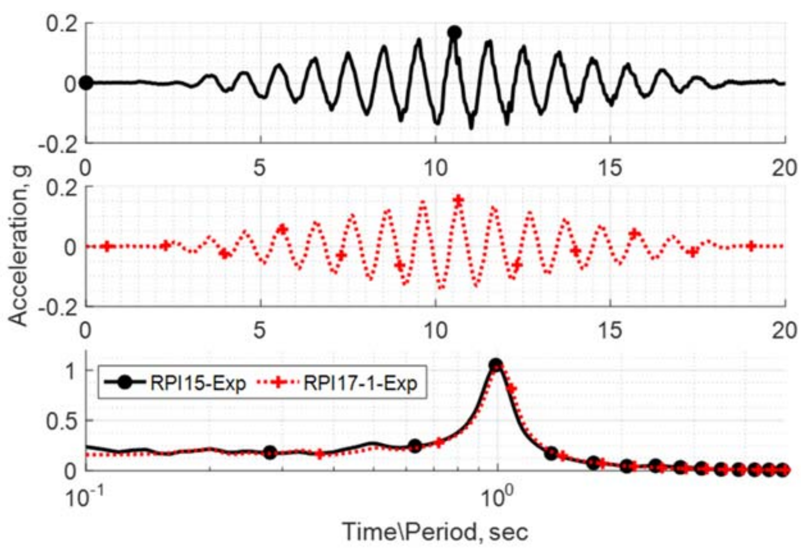

Figure 3: Time histories of the base motions achieved at RPI in LEAP-2015 and LEAP-2017.

A finite element mesh with 2048 quadrilateral u-p elements was used to represent the coupling of pore pressure and displacements in the submerged soil slope during the centrifuge spin-up and the seismic excitation. The excess pore pressure was set to be zero at the top free surface, the lateral displacements on the two side walls and both the vertical and lateral displacements on the bottom surface were fixed. Figure 4 shows a comparison of the computed excess pore pressure time histories with those measured in LEAP-2015 experiment. The pore pressure generation and dissipation phases as well as the maximum excess pore pressures at the locations of pore pressure sensors P1 to P4 are seen to be reasonably simulated.

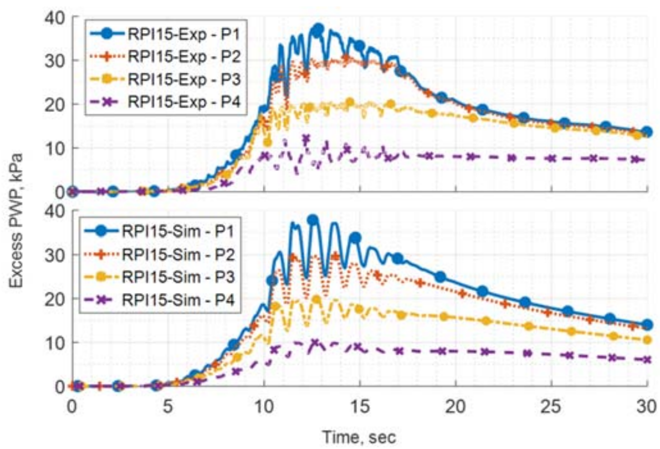

Figure 4: Comparison of the measured time histories of excess pore pressures at the location of P1 to P4 in RPI-LEAP-2015 experiment with the numerical simulations

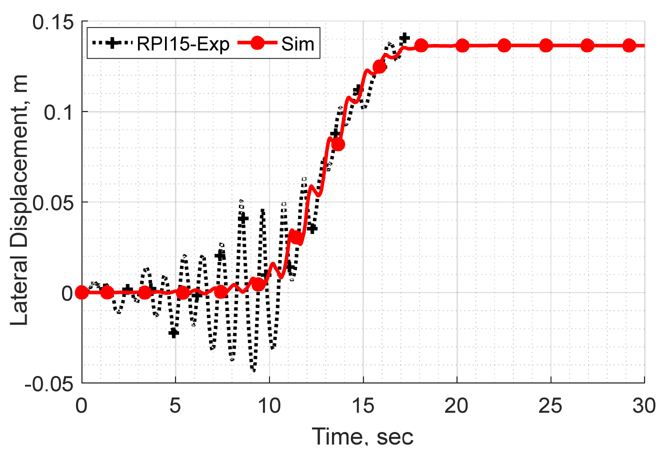

Figure 5. Comparison of the measured time history of lateral displacement in RPI-LEAP2015 experiment with the numerical simulations

4 Stochastic simulations

In addition to the deterministic finite element simulations, an example of which was discussed in the previous section, a large number of random finite element analyses using similar set-up were conducted to consider the effects of the spatial variability of soil density in the centrifuge specimens prepared for the validation purpose during the LEAP-UCD-2017 and LEAP-Asia-2019 projects. These simulations combined Monte Carlo simulation concept with nonlinear dynamic analysis of the centrifuge specimen (Figure 2). Moreover, since the achieved base excitations varied significantly among the different centrifuge facilities, the variability of the achieved base excitations was also included in the simulation by treating the base motion as a random process defined by the mean response spectrum and the covariance matrix of the spectral acceleration of the achieved base motions. A suite of base excitations that matched the mean response spectrum and the covariance matrix of the achieved base motions were generated and used in the random finite element analyses.

Figure 6 shows an example of the results obtained from these simulations where computed lateral displacements (black dots) are compared with the corresponding values measured at different centrifuge facilities (red and blue markers). The random finite element analysis results are seen to cover the range of the variations observed in the centrifuge experiments. It is particularly interesting to see that the numerical simulations show the same increasing trend with Arias intensity of the base excitations (I_a) as shown in experiments. It is also observed that both the computed and measured lateral displacements show a decreasing trend with the increase in cone penetration resistance (q_{c2}) which is a reflection of soil density. The cone penetration measurements are obtained by using miniaturized cone penetrometers in the centrifuge tests. Additional details about these comparisons are provided in ElGhoraiby and Manzari (2020).

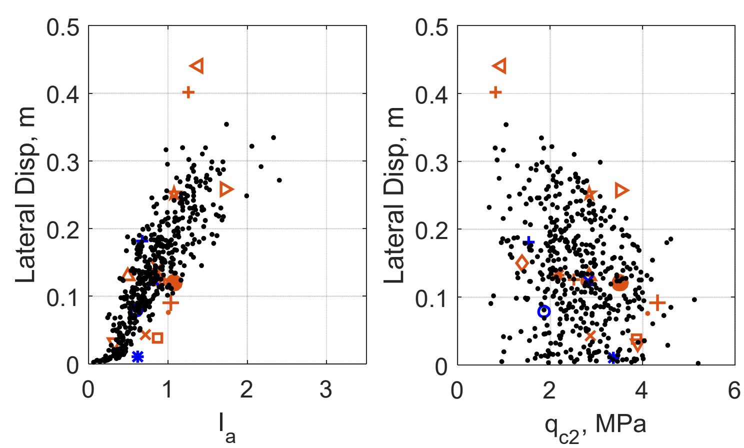

Figure 6. Comparison of the measured values of lateral spreading obtained in LEAP-UCD-2017 and LEAP-Asia-2019 with the computed values obtained from random finite element analysis

8 Conclusions

The deterministic and random finite element analyses conducted by using the critical state two-surface plasticity model show the capability of the model in simulation of a few key features of the soil response in liquefaction-induced lateral spreading phenomenon. However additional developments are required to improve the model performance in capturing the broad range of cyclic stress ratios that liquefiable soils may experience during earthquakes.

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