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LEAP Databases for Verification, Validation, and Calibration of Codes for Simulation of Liquefaction

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ABSTRACT

This paper introduces LEAP, Liquefaction Experiments and Analysis Projects, intended to facilitate validation and verification of numerical procedures for liquefaction analysis. The protocols and information necessary are organized and archived in a set of databases that contain the specifications for validation exercises and experimental data for calibration of constitutive models. The structure of the database is explained and the utility is demonstrated by populating the database with results from LEAP GWU 2015, an exercise that duplicated one liquefaction lateral spreading experiment on six different centrifuge facilities on three different continents. This data has already been used for Class A validation exercises and is also currently being used for class B validation exercises. The archived data will remain as a reference for future calibration exercises. Most importantly, a protocol is being established that will be useful in future validation exercises.

Introduction to LEAP and PLEAP

LEAP (Liquefaction Experiments and Analysis Projects) is an international collaborative project with a primary goal to develop a protocol for verification, calibration, and validation of numerical simulations used for analysis of liquefaction problems (Manzari et al. 2014). In addition to being a rigorous evaluation that is satisfying to simulation specialists, another goal of LEAP is to ensure that the limitations and scope of the validation and verification are understandable and conclusive for the engineers that use the results of the simulations as well as to decision makers that act on the results. PLEAP is a planning project funded under the Network for Earthquake Engineering Simulation (NEES) with the primary goal to lay the groundwork for future validation exercises.

The LEAP verification, calibration, and validation will be facilitated by data and documentation in a set of published databases, eventually with open public access. One database, described in

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conceptual detail by Kutter et al. (2014), is intended to archive verification simulations from a range of numerical models; it is envisioned that this database will archive solutions to simple benchmark theoretical problems, where the ability of different codes to model different physics (e.g., a critical state line, or coupling between fluid flow and solid deformations) is tabulated and graphically compared to results of other codes. One database will document standard sand properties (e.g., grain size, maximum density) and element test data (e.g., triaxial test data). Another database will include specifications for performance of validation experiments and instructions to predictors validating numerical procedures.

Class A, B, and C predictions will occur for most experiments. Adopting notation similar to that suggested by Lambe (1973), Class A predictions are completed prior to the experiment based on the experiment specifications; Class B predictions are completed after the event, with knowledge of the as-built properties of the experiment and actual input excitations; and Class C "predictions" involve after-the-event simulation of a known experimental result. Class C predictions may be more accurately viewed as calibrations.

One validation experiment involving centrifuge testing of a saturated sand slope (LEAP GWU 2015) was completed in January; the extensive experimental results from that exercise are documented in a fourth database. Six universities participated in the centrifuge tests: Cambridge University, UK; Kyoto University, Japan; National Central University, Taiwan; Rensselaer Polytechnic Institute, New York; University of California, Davis; and Zhejiang University, Hongzhou, China.

Overall Structure of the NEEShub LEAP Databases

Figure 1 illustrates the contents of the four aforementioned LEAP databases. These databases use the database tool developed by NEEShub <https://nees.org/resources/databases>. Allmond et al. (2014) is a good example of an already-published database on NEEShub.

LEAP verification simulations database

The verification simulations database, described by Kutter et al. (2014) is intended to accomplish two goals: (1) to describe the physics that the model is intended to simulate and (2) to demonstrate how the model captures the physics. This will be accomplished by defining a set of standard problems for which simulations produced by different solution schemes can be compared to each other and to closed-form solutions, if available. One example illustrates the implementation of Rayleigh damping, which can have profound effects on solutions. Another example, following the closed-form solution described by Jeremic et al. (2008), illustrates how the Biot formulation, often used to model dissipation of pore water pressures, is implemented. With regard to the verification of the constitutive model, verification examples would illustrate, for instance, the existence and uniqueness of a critical state line, the ability to model grain crushing, and the effect of static shear stress on the cyclic strength of the soil. The LEAP Verification Simulations database illustrates the physics modeled by different simulation platforms so that users are aware of their capabilities and limitations.

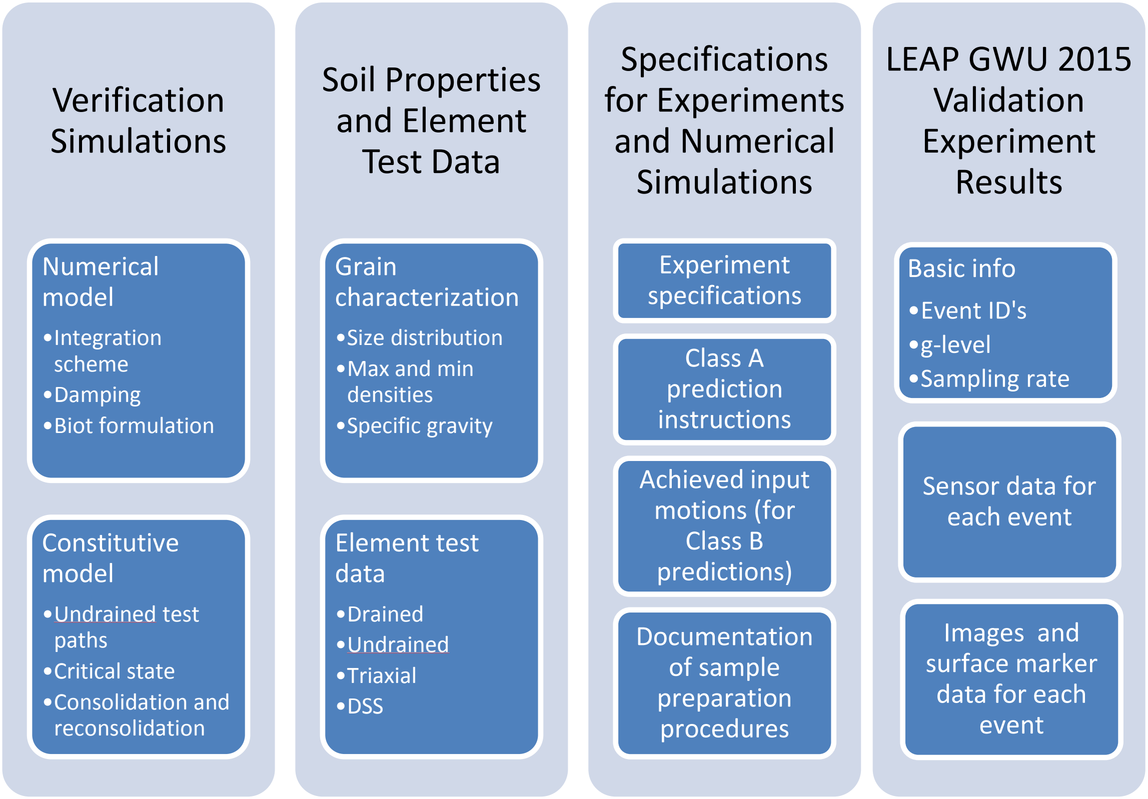

Figure 1: Outline and example contents of the four LEAP databases.

LEAP soil properties and element test data database

The LEAP Soil Properties and Element Test Data database presently contain experimental data to characterize Ottawa F-65 sand (and also Nevada Sand) used in validation experiments. Grain size distributions, index densities used to calculate relative density, and specific gravity are included. All of the data produced by different experimenters is included to help assess the reliability or uncertainty of the data. Each of these soil properties is to be referenced to specific batches of the sand, with the sources of the data, standard test procedures, and date of testing defined. The Soil Properties and Element Test Data database will also include, for a range of densities and confining pressures, results of element test data such as monotonic drained and undrained triaxial and direct simple shear tests, as well as cyclic tests to define the cyclic strength as a function of the number of cycles of loading. Examples of the monotonic drained triaxial tests are presented in Figure 2.

LEAP specifications for experiments and numerical simulations database

This database contains the specifications for different LEAP exercises. It presently only contains five fields: (1) LEAP name, (2) Experiment specifications, (3) Achieved input motions, (4) Specifications for Class A prediction, and (5) specifications for Class B predictions for the one LEAP event archived to date. The LEAP name identifies the name of the validation exercise. For example, the recently completed LEAP was called "LEAP GWU 2014," for which Class A predictions were presented at a workshop in January 2015.

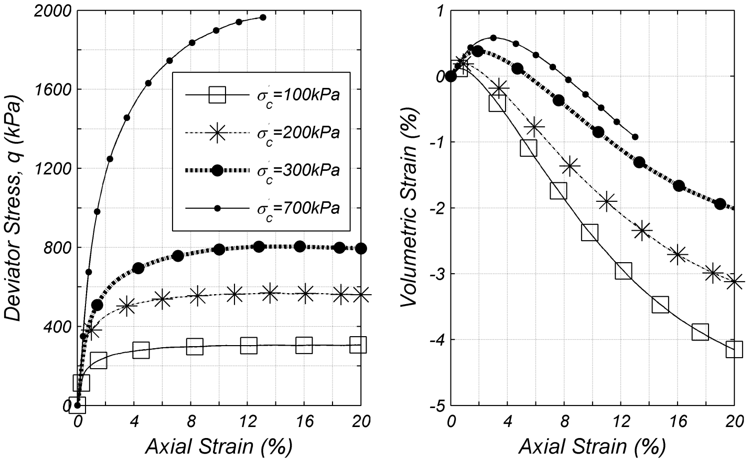

Figure 2: Examples of triaxial test data in the LEAP Soil Properties database (Vasko, 2015).

Experiment specifications

The experiment specifications may include multiple files used to specify the requirements for the experiments. For LEAP GWU 2015, the document evolved through several versions; the final specification was named Version 1.2 Model Specifications. This document included the scaling laws used, specification of the viscosity of the pore fluid, specification of Ottawa F-65 sand for the experiments, and a detailed procedure for saturation of the sand. The geometry of the sloping ground in the experiment and sensor locations were also specified, as illustrated in Figure 3.

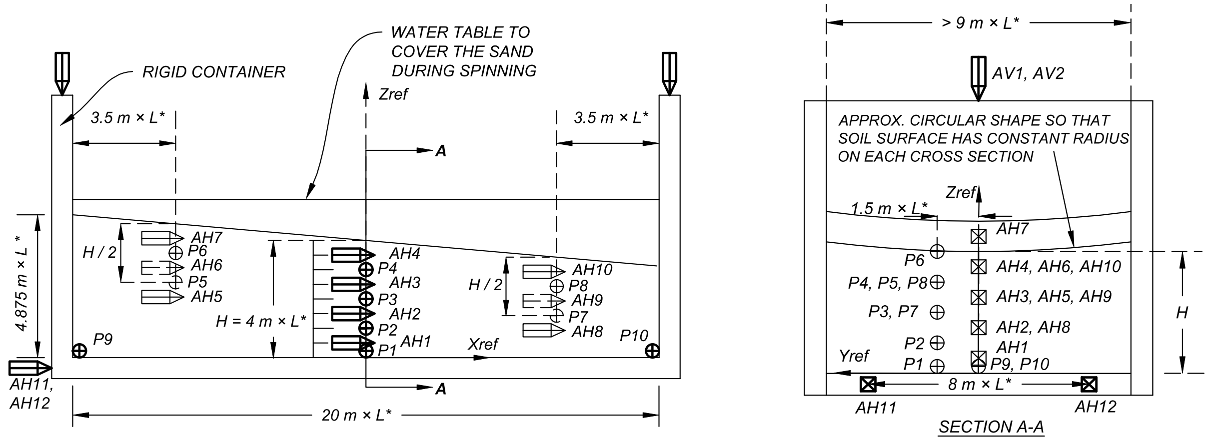

Figure 3: Surface geometry and sensor locations for GWU 2015 centrifuge test.

To improve the likelihood of successful duplication of results in multiple centrifuges in LEAP GWU 2015, it was decided to use the simplest possible container: a rigid container. A rigid container (example in Figure 4a) would avoid nuances associated with one-of-a-kind specialized containers such as flexible shear beam, laminar box, or hinged plate containers. The prototype scale is 20 m long and 4 m deep ground with surface sloping at 5^o. The length scale factor L* is determined by the width of the model container. Sensors are specified to detect horizontal, vertical translational acceleration as well as rocking and twisting accelerations.

These specifications were designed to be applicable to all six centrifuge facilities that performed the same experiment. Some of the centrifuges have hydraulic shakers that simulate 1-D horizontal shaking in the plane of rotation of the centrifuge, and others shake parallel to the axis of rotation of the centrifuge. The model specifications require a surface with radius of curvature equal to the radius of the centrifuge in the cross-section A-A in Figure 3, applicable for shaking parallel to the axis of the centrifuge. For centrifuges that produce shaking in the plane of spinning, the surface of the slope in the side view is superimposed on a curve corresponding to the radius of the centrifuge. The curvature is important, especially if reliable settlement data is required. In a centrifuge, if a soil liquefies, it tends to naturally form a surface curve of constant radius. If the soil is not curved prior to liquefaction, settlement will occur. The settlement is due to the formation of the curve, lateral spreading, and volume change during liquefaction. To avoid this error, especially for centrifuges with smaller radius, the initial curvature of the soil surface is critical.

The depths of the sensors are all referenced to the depth below the surface of the sand. The specifications described the placement of an array of surface markers on the ground surface, as illustrated in Figure 4b. The specifications also required a series of photographs and surveys of the surface markers to be performed at various stages of the experiment.

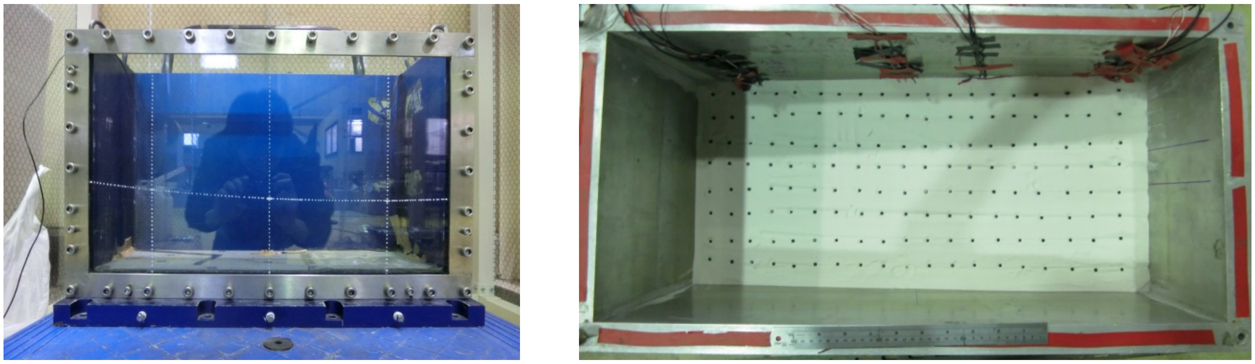

Figure 4: (a) Rigid container for centrifuge tests at Kyoto (left) and (b) the array of surface markers for the centrifuge tests at NCU (right).

As part of LEAP GWU, a sequence of earthquake ground motions were specified, as follows:

- Motion 1: 0.015 g nondestructive shake obtained scaling amplitude of Motion 2
- Motion 2: Peak Base Acceleration = 0.15 g, Peak Base Velocity = 0.226 m/s ramped sine wave (the main motion)
- Motion 3: 0.015 g nondestructive shake (repeat of Motion 1)
- Motion 4: The same waveform as Motion 2 scaled up by a factor of 1.67
- Motion 5: 0.015 g nondestructive shake (repeat of Motion 1)

Motions 1, 3, and 5 are intended to be identical, with the goal to allow characterization of the evolution of model stiffness after the main shaking events (Motions 2 and 4). Finally, the specifications included a template for submitting the sensor data and other information.

Class A numerical prediction requirements

This field of the database contains the document provided to numerical modelers to explain the experiment specifications. It also contains information about the format for reporting the results, some data characterizing the properties of the sand used, and directions for access to the cyclic and monotonic triaxial test data.

Class B numerical prediction requirements

For the Class A predictions, the results of Motion 2 were predicted with no knowledge of the experimental results. At the time of writing this paper, the instructions for Class B simulation are under development. For Class B predictions, the experimental results through Motion 2 are summarized and will be provided to all predictors along with the actual measured input motions for all of the important events.

Achieved base motions

The target motion and all the achieved base motions for the centrifuge testing at the six universities are presented in Figure 5. Closer agreement could be obtained by further calibration of the control systems for the shake tables, but time constraints prevented this calibration effort for some universities. The quality of agreement between the container base motions met or surpassed expectations of the authors, given the time constraints of LEAP GWU 2015.

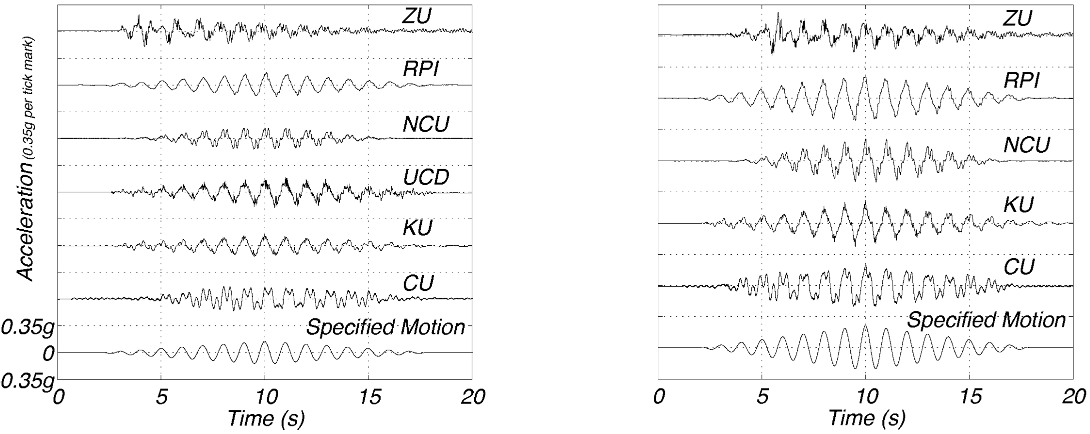

Figure 5: Achieved base motions for Motion 2 (left) and Motion 4 (right).

LEAP GWU 2015 validation experiment results database

This database contains data tables organized by the release date of the information. Prior to the Class A prediction exercise, no data is released; all the data needed for the Class A prediction is published in the database for Specifications for Experiments and Numerical Simulations. Prior to each prediction exercise, the appropriate results are to be published in the results database.

The March 2015 release of experimental data in this database includes sensor data and surface marker data for Motion 1 and Motion 2. Numerical modelers were asked to make Class B predictions of results for Motion 4. After the predictions for Motion 4 are submitted, all the data from all of the shaking events will be released.

LEAP GWU 2015 numerical simulation results database

Although this database has not been developed, a separate database is envisioned to archive the numerical simulation results.

Discussion

It is hoped that the databases will be interestingly populated to grow interest in their use to the point that the maintenance of the databases is self-sustaining. After the Class A and B validation exercises are completed for LEAP GWU 2015, the archived data will remain as a reference for future calibrations (Class C predictions). The protocols and specifications may be referenced for future LEAP validation exercises. Not only will the data continue to be useful for validation of numerical simulations, but it may also be useful for validation of experimental facilities. The ability of an experimental facility to reproduce results obtained previously at other experimental facilities could play an important role for facilities to assess and improve their own equipment and standards of practice.

A yet-to-be-solved issue is assessment of the quality of comparisons between experiment and simulation. An objective rubric for assigning pass/fail grades to a validation exercise or experiment remains elusive in some cases.

The input motions for the centrifuge tests performed for LEAP GWU 2015 were largely in good agreement with each other. Although experimental results are not identical, they are close enough to the specification to be useful for validation purposes. In fact, it will also be quite useful for one simulation model, with one set of material properties, to attempt to reproduce the differences between input motions from experiments on different centrifuges.

Conclusions

LEAP (Liquefaction Experiments and Analysis Projects) is an international collaborative project to develop a protocol for validation of numerical simulations used for analysis of liquefaction problems. It is hoped that LEAP GWU 2015 is only the first of a series of LEAP projects. The GWU 2015 exercise follows on the LEAP Kyoto 2013 and 2014 exercises organized by Professors S. Iai and T. Tobita. For the GWU 2015 project, a set of databases has been established for: (1) organizing the specifications for experiments and simulations, (2) providing the experimental data required for calibration of constitutive models, (3) archiving results of validation experiments, and (4) verifying constitutive models and numerical procedures.

LEAP GWU 2015 showed that multiple centrifuge facilities can adequately reproduce desired ground motions. For GWU 2015, a simple model configuration was chosen (submerged sloping ground in a rigid model container). Specifications for the experiment accounted for different sizes of available containers and different radii of the different centrifuge facilities involved. The results of the experiments are being compiled for later publication.

This paper presents some preliminary results from the GWU 2015 exercise to illustrate the contents of the database. The simultaneous development of the databases in parallel with the GWU 2015 validation exercise has resulted in a workable structure for the databases.

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References

Arulanandan, K; Scott, RF (1993-1994). "Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems," *Proceedings of the International Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Vols. 1 and 2, A. A. Balkema, Rotterdam, the Netherlands.

Allmond, JD; Kutter, BL (2014). JDA01: Centrifuge Testing of Rocking Foundations on Saturated and Submerged Sand, Network for Earthquake Engineering Simulation (distributor), Dataset, *Network for Earthquake Engineering Simulation* (distributor), DOI:10.4231/D37D2Q74Z.

Jeremic, B, Cheng, Z, Taiebat, M, and Dafalias, YF (2008). "Numerical Simulation Of Fully Saturated Porous Materials." *International Journal for Numerical and Analytical Methods in Geomechanics*, **32**(13), 1635–1660.

Kutter, BL; Manzari, MT; Zeghal, M; Zhou, YG; Armstrong, RJ (2014). Proposed outline for LEAP verification and validation processes. *Proceedings: Fourth International Conference on Geotechnical Engineering for Disaster Mitigation and Rehabilitation (4th GEDMAR)*, Kyoto.

Lambe, TW (1973). "Predictions in Soil Engineering," *Geotechnique,* Vol. **23**, No.2, pp. 149-202.

Manzari, MT; Kutter, BL; Zeghal, M; Iai, S; Tobita, T; Madabhushi, SPG; Haigh, SK; Mejia, L; Gutierrez, DA; Armstrong, RJ (2014). LEAP projects: Concept and challenges. *Proceedings: Fourth International Conference on Geotechnical Engineering for Disaster Mitigation and Rehabilitation (4th GEDMAR)*, Kyoto.

Vasko, A (2015). *Liquefaction Resistance of Ottwa Sand F65*, M.Sc. Thesis, Department of Civil and Environmental Engineering, The George Washington University, May.

Zeghal, M; Manzari, MT; Kutter, BL; Abdoun, T (2014). LEAP: Selected data for class C calibrations and class A validations. *Proceedings: Fourth International Conference on Geotechnical Engineering for Disaster mitigation and Rehabilitation (4th GEDMAR)*, Kyoto.