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LEAP: Data, Calibration and Validation of Soil Liquefaction Models

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ABSTRACT

The Liquefaction Experiments and Analysis Projects (LEAP) is an international effort to produce a set of high quality test data and then use it in a validation exercise of existing computational models and simulation procedures for soil liquefaction analysis. This article presents an overview of: (1) the requirements for calibration and validation data, (2) some limitations of existing calibration data, and (3) a recent LEAP validation exercise using a simple benchmark centrifuge model of a sloping ground deposit.

Introduction

Soil liquefaction is a pervasive problem during earthquakes. This problem is often associated with large permanent ground deformations leading to failure of soil systems of different types such as foundations, retaining structures, and embankments. Intensive efforts have been undertaken by researchers towards the development of constitutive and numerical modeling tools capable of predicting cyclic and permanent deformations of liquefaction prone soils (e.g., Zienkiewicz et al., 1998; Elgamal et al., 2003; Jeremic, et al., 2008). Significant advances were achieved over the past twenty years, in this regard, and there is currently an urgent need for validation and assessment of the reliability of modern numerical modeling.

The geotechnical community has been addressing the calibration and validation of computational tools for a long time through class A and C predictions. Lambe (1973) explained these predictions as follows: "A type A prediction of settlement, for example, would be made before construction and based entirely on data available at that time." "A type C prediction is one made after the event being predicted has occurred. The Profession is in great need of simple techniques to make type A predictions." "Type C predictions are autopsies." "…, one must be suspicious when an author uses type C predictions to 'prove' that any prediction technique is correct." With few exceptions (e.g., Arulanandan & Scott 1993, 1994), the geotechnical engineering community has relied mostly on class C predictions to assess the credibility of computational tools using problems for which the results are known before the assessment is made. Such predictions are valuable, but are often more calibration than validation efforts. Model validation requires class A (blind) predictions that ensure independence between computational and experimental results (Oberkampf et al., 2010). The engineering community will become more confident in the geotechnical computational tools only if class A predictions are systematically used with standardized validation methodology and metrics. The Liquefaction Experiments and Analysis Projects (LEAP) is an international effort to produce high quality experimental data sets and undertake a systematic exercise to validate existing computational models of the response and liquefaction of saturated granular soils (Manzari et al., 2014 and Kutter et al., 2014).

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This article discusses some of the requirements for an effective model calibration and validation and gives an overview of LEAP and a recent validation effort that included centrifuge tests and blind predictions in Asia, Europe and the USA.

Soil Liquefaction Analyses and Validation Needs

The dynamic response of saturated granular soils is complex and exhibits patterns associated with the particulate discrete nature of these soils and the effects of pore pressure buildup. Numerous computational tools were developed over the last decades, and are now able to handle a multitude of response mechanisms associated with excess pore pressure buildup and liquefaction with different levels of realism. The developed tools are often calibrated through personal efforts using class C predictions. These efforts are generally limited and may lack consistency due mostly to an absence of coordination. Thus, there was no thorough assessment and validation of computational tools used to analyze soil liquefaction. The one-time EPRI (1993) initiative and VELACS (Verification of Liquefaction Analyses by Centrifuge Studies) project (Arulanandan & Scott, 1993 and 1994) were possibly the only exceptions. This 1990s project involved 12 models that were tested at 7 centrifuge facilities and over 20 numerical modeler teams who participated in class A predictions. This exercise showed significant variability in centrifuge experimental results and numerical predictions.

The past two decades witnessed significant advances in centrifuge testing and experimental simulations of the response and liquefaction of saturated soil systems when subjected to dynamic loading. In the USA, the NEES (Network for Earthquake Engineering Simulation) initiative has been instrumental in upgrading the experimental facilities for earthquake engineering research (NEES 2015). These two decades were also marked by tremendous advances and developments of sophisticated constitutive and numerical modeling techniques. However, these advances and developments were achieved quite often independently of the progress in experimentation and testing of soil systems. Thus, our computational tools are either not able or have not been properly validated to address a number of challenging, but common, liquefaction phenomena, such as large lateral deformations and void redistribution. The effects of multi-axial shaking, shear bias and pre-shaking, and influence of soil fabric are also associated with other complex liquefaction mechanisms that still necessitate attention from the computational geotechnical community. There is currently an urgent need for coordinated validation efforts to assess the capabilities and accuracy of computational tools used to predict the liquefaction phenomenon and its consequences on civil infrastructure systems. LEAP is an ongoing international effort to produce high quality experimental data sets and to validate existing computational models of the dynamic response and liquefaction of saturated granular soils (Manzari et al., 2014). Achieving the objectives of this effort requires: (1) consistent standard for the validation of computational tools (Kutter et al., 2014), and (2) a comprehensive set of a high quality reliable experimental data. A thorough validation of these tools using case history analysis of full-scale systems often requires significant assumptions and may not be practical or feasible (Zeghal et al., 2014). The alternative is to use experimental data provided by tests of soil samples and small-scale centrifuge models under controlled conditions.

Requirements for validation data

The majority of experiments in geotechnical engineering are conducted primarily to: (1) advance the fundamental understanding of some physical phenomena (e.g., lateral spreading or void redistribution), (2) improve or possibly construct a mathematical model of these phenomena, or (3) assess the performance or safety of an engineering system (or subsystem). These experiments are often not adequate for specific validation tasks because of a number of reasons, including: (1) inconsistency between the validation objective and the experiment, (2) limited resolution of measurements of response quantities (e.g., only global response parameters are measured), or (3) incomplete documentation of testing conditions (e.g., incomplete measurements of input quantities). A validation effort to assess the applicability and accuracy of a computational tool requires the design and conduct of specific experiments. Specifically, these experiments should be planned to capture clearly the essential physics of the phenomena of interest, and measure with adequate resolution and level of accuracy all response, initial and boundary condition parameters necessary to perform the validation. The purpose is to acquire data that enable a quantitative and conclusive assessment of the ability of the computational models with as little assumptions as possible. Furthermore, the validation has to be performed in an independent fashion of the experimental procedures and tests to ensure an “objectivity” of the assessments. Within the context of a community projects such as LEAP, the requirements above are achieved by relying on close collaboration and coordination among experimentalists and computational modelers to design adequate validation experiments and use mostly blind (class A) predictions (Oberkampf et al. 2010).

Experimental Data for Calibration and Validation

A quantitative calibration and validation of computational tools to predict specific aspects of soil response associated with liquefaction is contingent on the availability of adequate experimental data. Development of reliable experimental centrifuge test data is an essential goal of LEAP. Liquefaction problems are complex and marked by the presence and coupling of different physics related to the soil solid and fluid phases and interaction with any relevant foundation or structural element. A hierarchical strategy is used in LEAP to address this complexity in validating soil liquefaction models. This strategy divides the validation problem into a series of progressively more complex sub-validations (Oberkampf et al., 2010). Furthermore, soil liquefaction models would generally require a calibration step (prior to validation) since some of the associated physical parameters cannot be measured directly from experiments (such as those controlling void redistribution and changes in permeability). The employed strategy consists of: (1) model calibration using class C predictions and data of single element tests and centrifuge model experiments, and (2) validation using class A blind predictions and centrifuge test data of benchmark models (e.g., level sites and simple slopes) and a series of soil systems with increasing level of complexity (e.g. dams, soil-structure systems, etc.). The benchmark models will be employed to assess the ability of constitutive and numerical tools to simulate fundamental aspects of soil response, such as the transition from a contractive to a dilative behavior and the effects of shear stress bias or fabric on the initiation and evolution of soil liquefaction. The system tests will be utilized to evaluate these tools under more complex settings, such as within the context of soil interaction with structural elements. Numerous experimental investigations were conducted over the last decade to study the mechanisms of soil liquefaction during earthquakes and its effects on the response of civil engineering infrastructure. The experiments that were conducted and curated within the context of NEES (George E. Brown Network for Earthquake Engineering Simulation) are a noteworthy example. These experiments include both centrifuge and full-scale tests (NEES 2014) and provide an unprecedented wealth of good quality data. Some sets of this data are good candidates for class C predictions (or calibrations) of liquefaction computational tools, but do not provide self-contained high quality validation data sets. The shortcomings are primarily because the experiments are not duplicated at multiple facilities (i.e., there is no assessment of uncertainty) and in some cases the experiments are too complex and cannot be used in validation of a liquefaction problem without additional experimental data.

Uncertainties are always present in experimental data and the validation process cannot assume that this data is fully correct. The model predictions may be credibly assessed and used in quantitative validations only if the accuracy and uncertainty in measured experimental data are explicitly taken into consideration (Oberkampf et al., 2010). There are different types of factors that lead to uncertainties in complex experiments such as centrifuge tests. These factors include experimental setup, instrumentation and procedures, along with the testing facility characteristics. The uncertainties may be of systematic or random nature (Oberkampf et al., 2010). Quantification of experimental errors and biases has always been a challenge in testing of geotechnical soil elements and systems. Thus, these errors were often acknowledged, but rarely explicitly considered in validation of (geotechnical engineering) computational tools. Experimental errors associated with sensor limitations (e.g., accuracy or precision) are presumed to be minor in view of a significant advance in sensing technology. However, there is always variability in experimental results associated with the different testing procedure used at separate facilities. The LEAP project relies on replication of tests and modeling-of-the-model to assess the associated level of biases and experimental errors.

Calibration Data: Case Study of Quality Evaluation and Assurance

A benchmark test of a level site (Gonzalez, 2008) was selected from NEES-hub to illustrate some aspects of the analyses that may be used to assess the quality and appropriateness of data for model calibration and validation. Briefly, the test consisted of about 6 m (in prototype units) of a Nevada sand deposit tested in a laminar box (Figure 1). The soil had a relative density of 40 % and saturated with a viscous fluid to achieve a permeability of the order 10^{-4} m/s. The soil model was equipped with an extensive array of accelerometers, pore pressure transducers and LVDTs. The deposit was subjected to a base excitation that consisted of 4 phases with relatively constant acceleration amplitudes which increased with phase (Figure 2). The recorded pore pressures (Gonzalez, 2008) showed that the soil experienced high (pore pressure) ratios during the third and fourth phases of excitation starting at about 16 s. Nevertheless, during these phases the accelerations measured on the laminates showed a response more consistent with the input motion than the soil response (with remarkably large accelerations during the fourth shaking phase when the soil had fully liquefied, as shown in Figure 2). In other words, the laminates are not fully frictionless, and the interlaminate contacts are able to transmit significant accelerations.

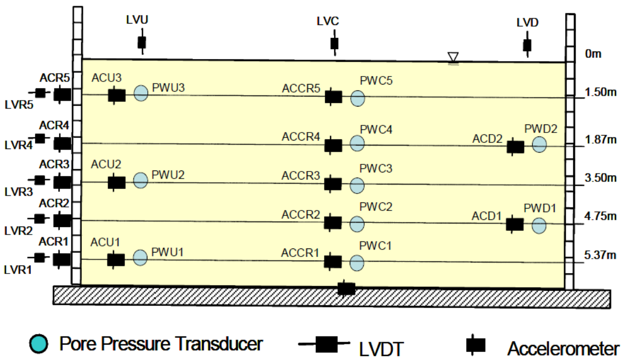

Figure 1: Schematic of a NEES level ground centrifuge test conducted using a laminar box.

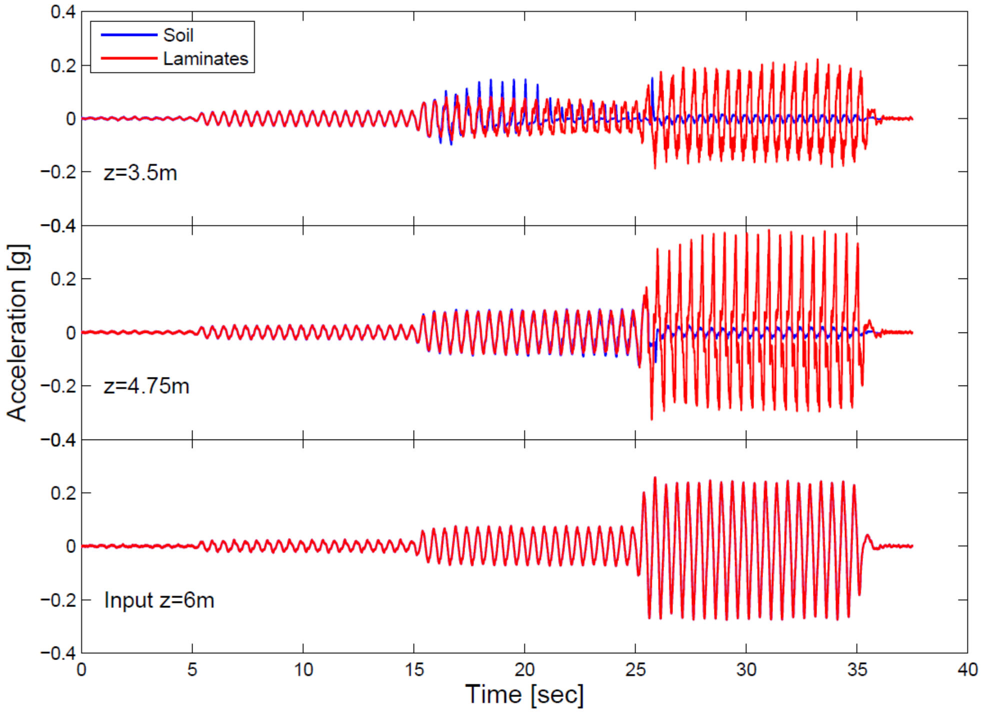

Figure 2: Input acceleration and accelerations recorded at 3.5m and 4.75 m depth of the model of Figure 1.

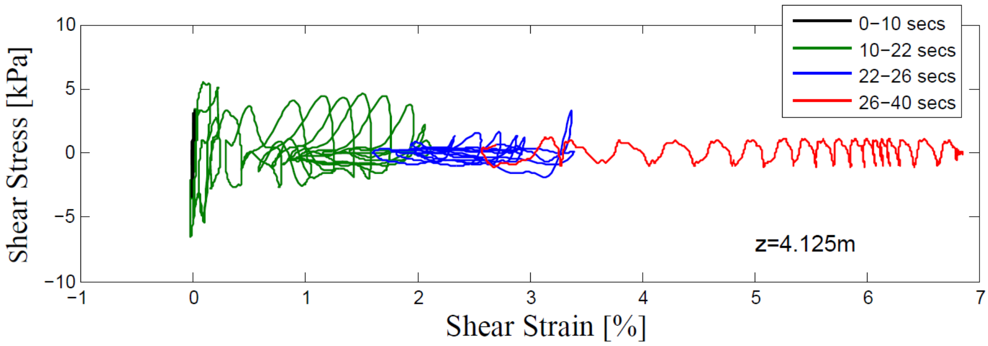

Figure 3: Shear stress-strain response (at about 4.1 m depth) of the model of Figure 1.

The recorded accelerations within the deposit and permanent lateral displacements of the laminates were used to obtain the soil shear stress-strain response (using a technique developed by Zeghal et al., 1995), as shown in Figure 3. The evaluated stresses and strains assume that the soil response within the central part of the deposit is dominated by shear-beam type deformations. Figure 6 shows this assumption to be valid until about 26 s of shaking, and that the associated response was marked by a number of significantly dilative cycles during the 10 s to 22 s window. During the last phase of shaking (22 s to 26 s), the estimated shear stress-strain response had a significant amplitude and a pattern not consistent with that exhibited during the 10 s to 22 s window. Apparently, once the soil liquefied fully (i.e., pore pressure ratio of about 1.0), a significant portion of the measured soil accelerations were transmitted through the container laminates and normal waves through the soil. Thus, the permanent lateral displacements accumulated during this phase do not reflect the soil response. This finding indicates that a thorough quantitative calibration or validation exercise using the soil model shown in Figure 1 may require a realistic model of the laminar container that reflects the actual inter-laminate friction coefficient and the interaction between the soil and the laminates (both in the normal and tangential directions).

Validation Data and the LEAP 2015 GWU Exercise

A validation effort (denoted LEAP 2015 GWU) was undertaken in 2015 using a benchmark centrifuge model of a sloping deposit (Figure 4) that was selected taking into consideration the above discussion and observations. Briefly, the model corresponded to a prototype deposit having a length of 20 m and a height decreasing from 4.875 m to 3.125 m (or a 5^o slope). The test was conducted at six centrifuge facilities, namely Cambridge (University), (University of California) Davis, Kyoto (University), Rensselaer (Polytechnic Institute), Taiwan (National Central University), and Zhejiang (University). These facilities used different (centrifugal) g levels and physical model dimensions to achieve the same target prototype dimensions. The same Ottawa F-65 sand was used and an extensive set of material and element tests were conducted to characterize this soil and provide data necessary for constitutive model calibration. A the different facilities, the soil was deposited by dry pluviation (with a target dry density of 1652 kg/m^3) and the models were saturated with viscous fluids to attain the same prototype permeability corresponding to 1 g condition. The models were equipped with an extensive array of accelerometers and pore pressure transducers (Figure 4). Markers were employed to measure the surface settlements and lateral displacements after the end of shaking. One of the sites used a high speed camera to monitor these displacements during shaking. The models were subjected to a series of successive excitations that included a first nondestructive 0.015 g motion followed by a 0.15 g motion (Figure 5). Concurrently to the experimental program, a series of class A blind predictions were undertaken at Virginia Tech, the University of Washington, and by practitioners in the USA and Japan. The recorded response parameters at the six different centrifuge facilities and the outcome of the class A predictions are currently being analyzed and curated within a databank (Kutter et al., 2015) and will be published subsequently along with the details of the experimentation and numerical efforts.

Herein, a sample of the results of an ongoing identification and characterization analyses are presented to illustrate the range of response conditions that were associated with the benchmark test (Figure 4). The accelerations, surface displacements, and excess pore pressures, recorded at Rensselaer, were employed to evaluate the shear stress and strain histories at several depth locations along the installed arrays (as shown in Figure 6 for the central array). The shear stress histories were marked by the presence of large spikes associated with a dilative response when the deposit experienced large shear strain excursions in the downslope direction (Figure 7). The associated permanent shear strains were estimated be of the order of 2.5 % at a depth of 2 m along the central array. The evaluated stresses and strains showed a high level of consistency that is apparent trough the stress-strain history and (vertical) effective stress-shear stress path. The observed response provides good quality data for a validation of computational models of soil liquefaction and transition from a contractive to a strongly dilative behavior during dynamic loading. Additional analyses are underway to assess further the quantity of recorded data and estimated stress and strain paths.

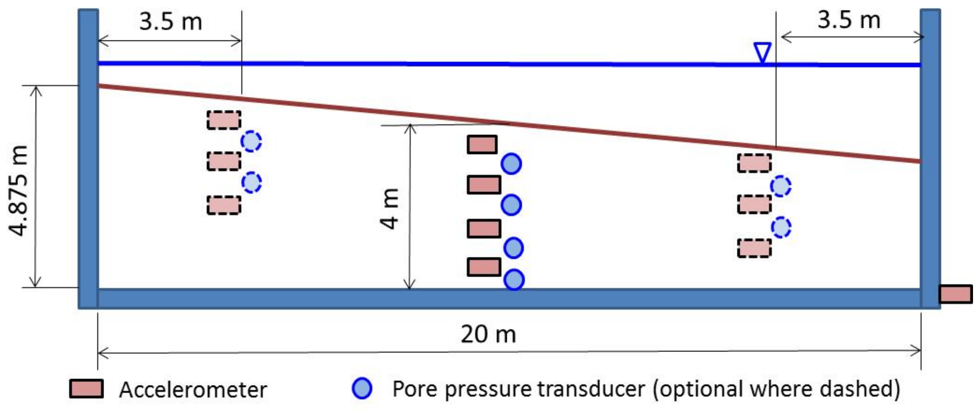

Figure 4: Schematic of the centrifuge model of the LEAP 2015 GWU showing a sloping deposit tested using a rigid box (all dimensions are in prototype units).

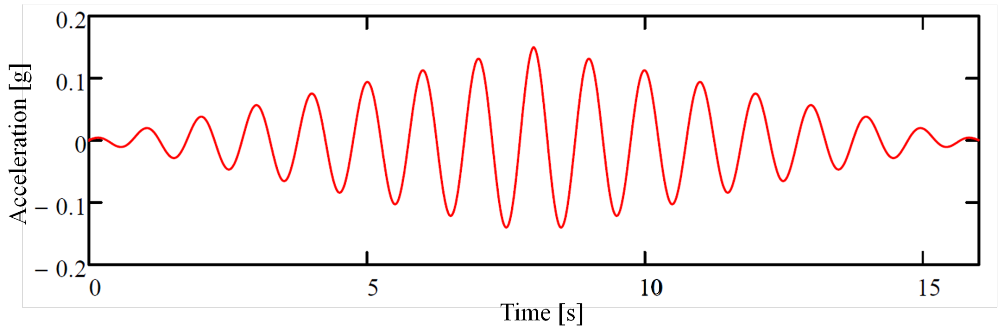

Figure 5: Input acceleration of the centrifuge model of Figure 4 (motion 2 of LEAP 2015 GWU).

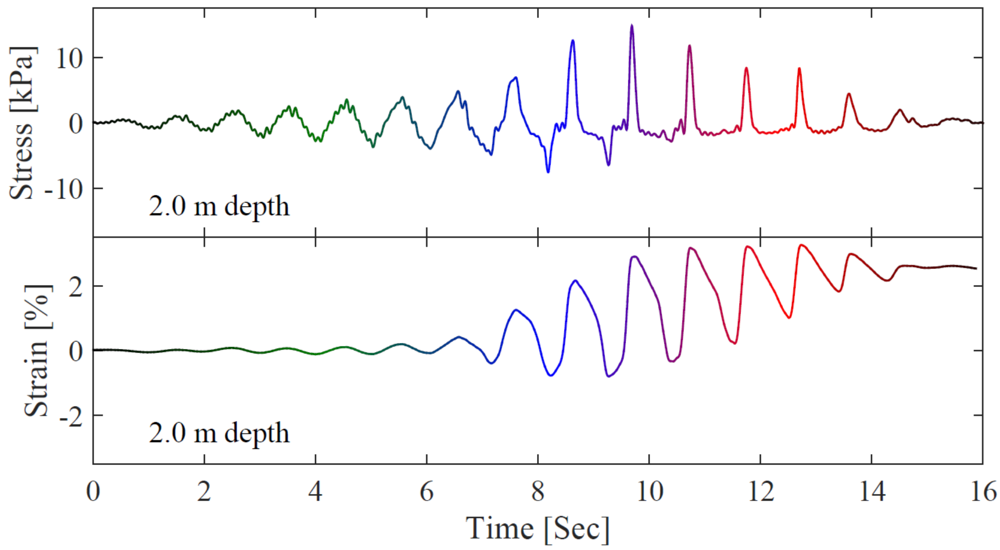

Figure 6: Estimates of the shear stress and strain time histories of the LEAP 2015 GWU test conducted at Rensselaer.

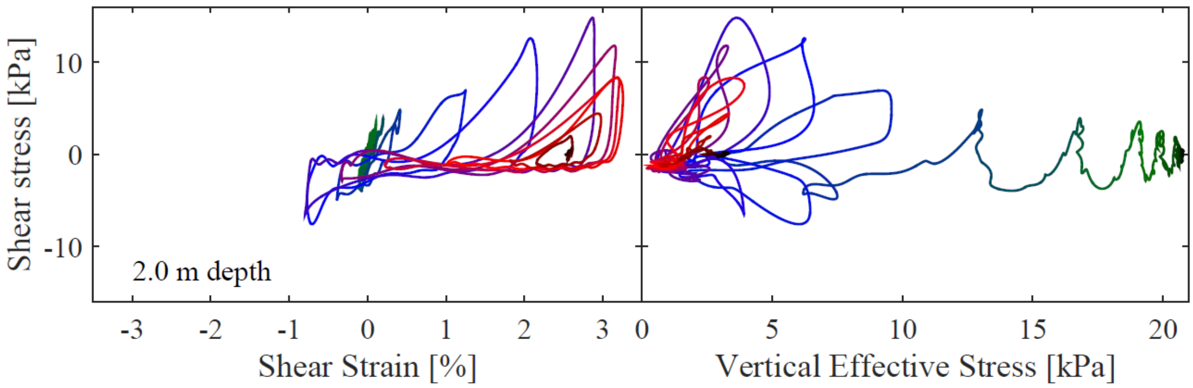

Figure 7: Estimates of the shear stress-strain and effective stress paths of the LEAP 2015 GWU test conducted at Rensselaer.

Conclusions

This article presented an overview of the international effort LEAP (Liquefaction Experiments and Analysis Projects). These are projects to produce high quality experimental data sets and to undertake a systematic validation of existing computational models of the dynamic response and liquefaction of saturated granular soils. A number of issues related to the characteristic of experimental data that may be used in LEAP calibration and validation tasks were discussed. A validation effort was initiated in 2015 using a benchmark model of sloping deposit tested at six different centrifuge facilities and blind predictions by a number of modelers. Ongoing analyses of the (benchmark) experimental results showed a response marked by large deformations and a transition from contractive to a highly dilative behavior and providing good quality data for a validation of computational tools.

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