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LARGE-SCALE HYBRID SIMULATION OF SOIL-FOUNDATION-STRUCTURE-INTERACTION IN A GEOTECHNICAL LAMINAR BOX

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ABSTRACT

Soil-Foundation-Structure-Interaction (SFSI) is a necessary consideration in the design of nuclear facilities. Laboratory studies of SFSI at an element scale or reduced-scale are challenging as realistic boundary conditions are not replicated appropriately, and the response of integrated sub-systems and agglomerated soils are prone to scaling issues, particularly when pore fluid is present. Large-scale testing with real-time dynamic hybrid simulation is a useful tool for characterizing SFSI effects. By increasing knowledge of the fundamental physics and parameters that drive SFSI phenomena, new and existing nuclear facilities will be better analyzed and designed (or retrofitted) to achieve target performance goals at the component and systems levels.

In this study, the Geotechnical Laminar Box at the University at Buffalo was used to create a large-scale model of a liquefiable soil column and pile foundation system, upon which a hybrid shake table was installed. The parametric experimental program included three inputs: base motions, superstructure only motions, and hybrid scenarios involving the base and superstructure. More than 150 seismic events were executed on the large-scale model to characterize the response of the soil-structure system. Novel sensing technologies were employed to identify the state of the soil and soil-foundation system between successive seismic events. This paper describes the initial findings of the hybrid SFSI setup and identifies areas for further research.

INTRODUCTION

This paper expands on the findings of Stefanaki et al. (2015), which introduced the first physical experiment at the University at Buffalo (UB) involving a Geotechnical Laminar Box (GLB) and a Hybrid Shake Table (HST). Since that time, two additional GLB experimental programs have been executed in 2015 and 2016. The experiments in 2015 continued the hybrid testing of 2014; the 2016 experiments involved partially saturated sand with no hybrid component to characterize free-field conditions. The focus of this paper is the 2015 experiments.

The main conclusion of Stefanaki et al. (2015) is that to accurately mimic superstructure dynamics, the HST system should be actively controlled in real time. Since then, the HST and its real-time capabilities have been validated (Stefanaki 2017). Hybrid simulation has been investigated by many structural engineering experimentalists; a history of methodologies developed is described by McCrum et al. (2016).

The purpose of GLB-HST experimentation is to investigate the challenges related to soil-foundation-structure interaction (SFSI) and the key parameters that influence superstructure dynamics, foundation, soil, and pore-water response (Stefanaki et al. 2015). By gaining a more thorough understanding of SFSI, it will be possible to better analyze and design for nuclear facilities, including nuclear power plants.

In the past, simple approaches involving lump-mass setups have been used to model structural dynamics in large-scale geotechnical laminar box shaking, e.g., Suzuki et al. (2008) and Motamed et al.

(2013). However, limited work has involved the hybrid shaking and geotechnical models. Kong et al. (2015) examined (pseudo-static) real-time hybrid simulation at the centrifuge level, and Ojaghi et al. (2010) investigated hybrid testing at the centrifuge level via a "distributed" network. However, scaling mismatch between dynamic time (proportional to the g-level) and diffusion time (proportional to the g-level squared) is always a concern when using a centrifuge. Large laminar boxes, like the UB GLB, help move the research away from these scaling issues, while still allowing room for an HST system.

Kobayashi et al. (2002) demonstrated a hybrid experiment with a pile-founded bridge pier dynamically loaded in a 3-m (118-in) tall laminar-box soil column. Even though this experiment was not real-time in-the-loop hybrid testing, this bridge-pier experiment is similar to the methods developed at UB. Further, the majority of recent advancements have been in the algorithms that control the hybrid coordination. Computer systems work in conjunction with the physical system to create a dynamic interface that more realistically represents and measures the at-hand structural dynamics. Since nuclear facilities are sensitive to interface impedances, i.e., changes in boundary conditions of the soil-foundation-structural system, an appropriate recreation of these is critical in understanding the global response.

Hybrid simulation is a closed-loop test that requires structural response feedback, e.g., restoring forces and displacement responses to determine the loading command for the next time step (Shao et al. 2013). The UB HST system imposes desired structural scenarios on the physical system and at the same time monitors changes, e.g., acceleration and displacement, within the physical system to update the computer algorithm. The system has been used to identify differences in dynamic soil-pile interaction through changes in the foundation-superstructure impedance.

VALIDATION OF THE HYBRID SYSTEM

The SMiRT23 paper showed that the GLB-HST system was feasible and that using a controllable foundation system in the GLB provides a new, applicable method for testing SFSI. Comparisons of several theoretical, i.e., mathematical models, and experimental setups were used to confirm that the system runs correctly. Refer to Stefanaki (2017) for a complete description of how this was accomplished.

The overarching goal is to have complete control of the HST and provide the ability to couple any type of virtual superstructure with the GLB-HST model. Thus, the system was designed to be flexible, where any condition can be imposed, from realistic physical structures to artificial worst-case impedances. The HST is capable of executing any desired structural-dynamic scenario. For example, in a series of tests, the HST was fixed on top of low-stiffness elastomeric bearings and dynamically shaken by one of the UB Structural Engineering and Earthquake Simulation Laboratory's six degree-of-freedom (DOF) shake tables, as shown in Figure 1. In this case, the HST represents some virtual superstructure, the bearings represent some resonant-physical subsystem, e.g., a soil stratum, and the 6-DOF shake table represents some base or "bedrock" motion. Because the impedance of the elastomeric substructure is well known, since it is a manufactured material/component, the HST response can be validated against the theoretical model. The transfer functions derived show that, for a particular set of boundary conditions and desired superstructure dynamics, the experimental data (red) and expected response of the mathematical model (blue) match well. Confidence in the controls and frequency response of the HST under known conditions allows the system to be used in the GLB for real-time in-the-loop actively controlled hybrid testing of geotechnical models. A full real-time in-the-loop GLB-HST test set is slated for late 2017.

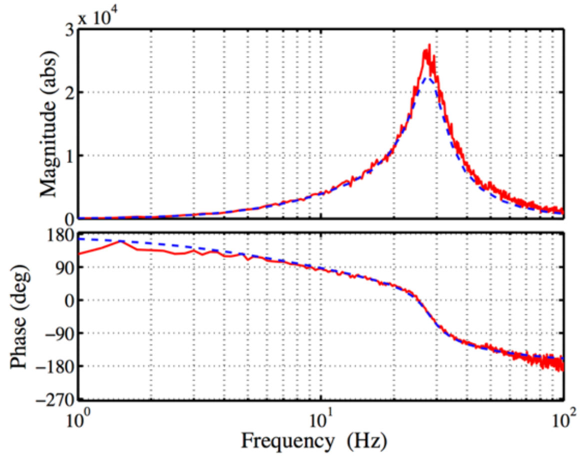

Figure 1 – Left: Photo of HST Validation Setup; Right: Example Validation Transfer Functions

Validation of the HST system enables confidence in understanding any physical subsystem, e.g., a soil-foundation system in the GLB. The principal advantage of the UB HST system is that it does not require prior or pre-programmed knowledge of the soil or subsystem. It can impose any forces or displacements on the base, which makes it particularly well suited for parametric studies in the GLB. The same test type of plan was carried out for the 2015 experiment described in the research of Stefanaki et al. (2015). However, this new test provides further insight into using the GLB-HST system as well as providing new and more comprehensive data, and will be explained in the next two sections.

FURTHER PARAMETRIC STUDIES: GLB-HST EXPERIMENTAL SETUP AND EXECUTION

For GLB experiments, Ottawa F55 sand is placed into the 82-m^3 GLB vessel using a dredging pump submerged in outdoor storage tanks via a hydraulic-fill process. The sand placement in the GLB is conducted with a few extra feet of water and is placed similarly to natural deposits (Thevanayagam et al. 2009). Since the material is placed hydraulically, it is generally loose, i.e., near the maximum void ratio, and "weak" prior to any base motions. The 2015 hybrid test was conducted with a fully saturated soil column. Partially-saturated setups are possible by pumping water out via deep wells.

As mentioned in the SMiRT23 paper, the geotechnical hybrid-shaking physical subsystem developed at UB, to date, consists of the HST attached to a pile foundation, which has been driven into the GLB soil column. The foundation system between the HST and soil can be changed, e.g., to a shallow footing. Additionally, different soil profiles can be fabricated in the GLB using different materials, e.g., gravel, silt or clay. The 3D model in Figure 2 shows, via a cutaway, the layout of a GLB-HST setup. This depiction is an exact replica of the GLB-HST setup and will be used in computational software to pair with experimental results. Note the red and yellow components represent embedded instrumentation in the soil column.

Similar to Stefanaki et al. (2015), the parametric study involved imposing various motions on the model. First, a lump-mass investigation was conducted. This process involved shaking the bottom of the GLB with sinusoidal motions of varying frequency and amplitude. By only shaking the base of the GLB, this lump-mass scenario serves as a typical control or base case. During this first test phase, shaking was used to consolidate the soil column. Again, the geomaterial is very loose after hydraulic placement. Consolidation proceeded on the GLB soil column until the HST was able to support its own weight. Consolidation of the soil column provided a comprehensive set of embedded test data on purely-soil consolidation and insight into liquefaction. Furthermore, these motions enabled testing and adjusting of the new in-situ and external sensing systems. After this initial phase, shaking motions were applied to the HST only, while keeping the base of the GLB stationary. Labeled as a "machine foundation" motion, this represents a machine or structure imposing energy into the soil column. Gapping between the piles and soil near the surface was observed, and the system was sensitive to this phenomenon. The final GLB-HST phase consisted of dual motions that included loading the bottom of the soil box with also running various virtual superstructure scenarios.

Coupling between the soil base motions and the hybrid motions enables analysis of the SFSI phenomena. The research herein seeks to obtain preliminary data on the combinations of superstructure and base motions most likely to result in damage. This is a continuation of the parametric study presented in SMiRT23, as well as in Stefanaki (2017).

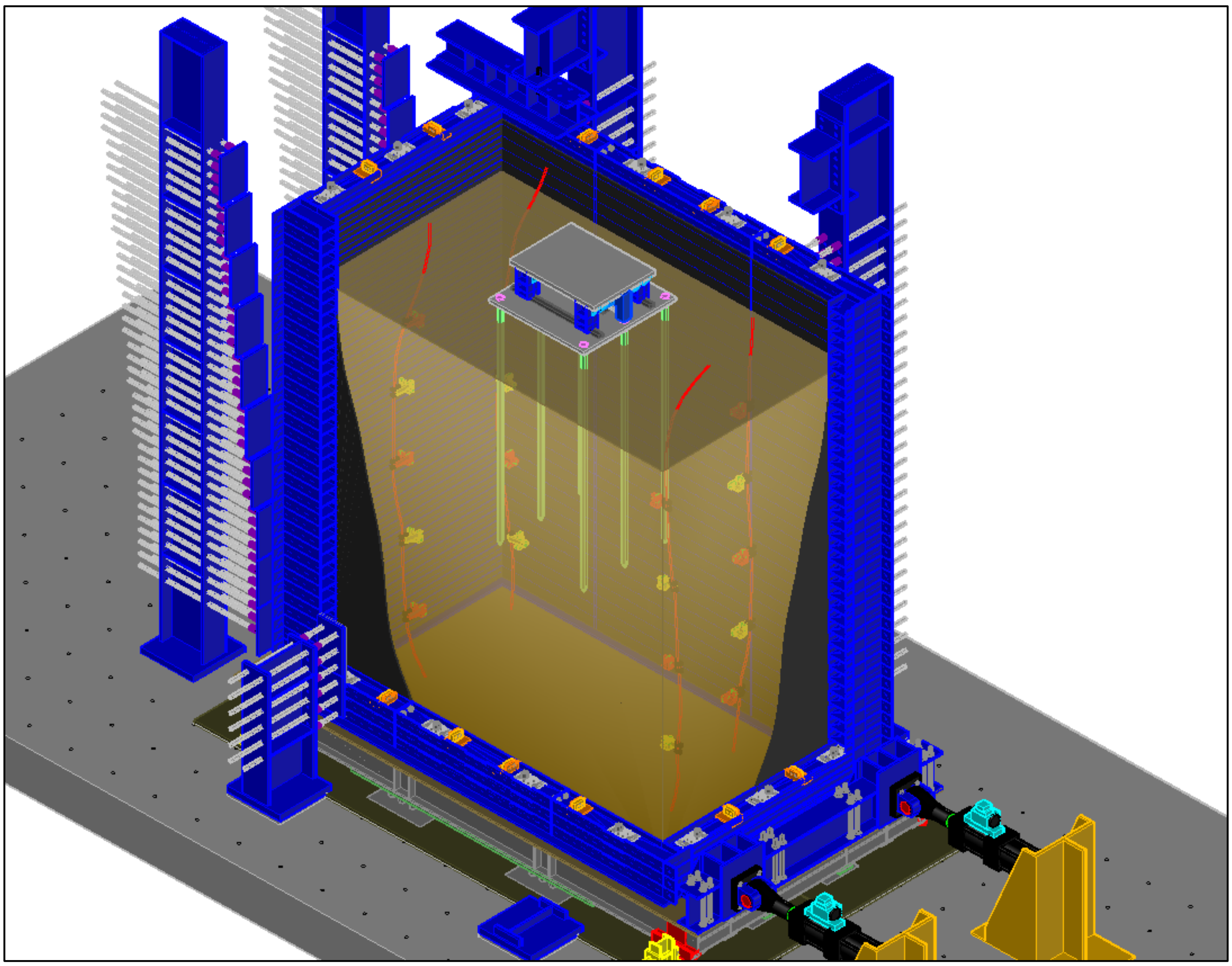

Figure 2 – Three-Dimensional Computer Model of UB GLB and HST Setup

In the previous report, the box and table were controlled separately with the predicted response of the structure serving as the control. In this paper, the HST system utilizes real-time in-the-loop feedback algorithms, which could impose any desired response at the foundation-soil system with confidence. The flow chart below (Figure 3) shows the procedure of our new capabilities. In summary, the GLB motion and HST are triggered by a common signal. As the GLB-HST motion proceeds, the HST system creates the desired dynamics in the model in real time. The flexibility of this setup is that any hybrid motion, and therefore any virtual superstructure, can be imposed.

Data is collected over the height of the soil column by monitoring acceleration and displacement time histories of the laminates. The thickness of each soil-shearing layer is 152.4 mm (6 in), e.g., there is a 1.219-m (48-in) on-center distance between Laminate 6 and Laminate 14.

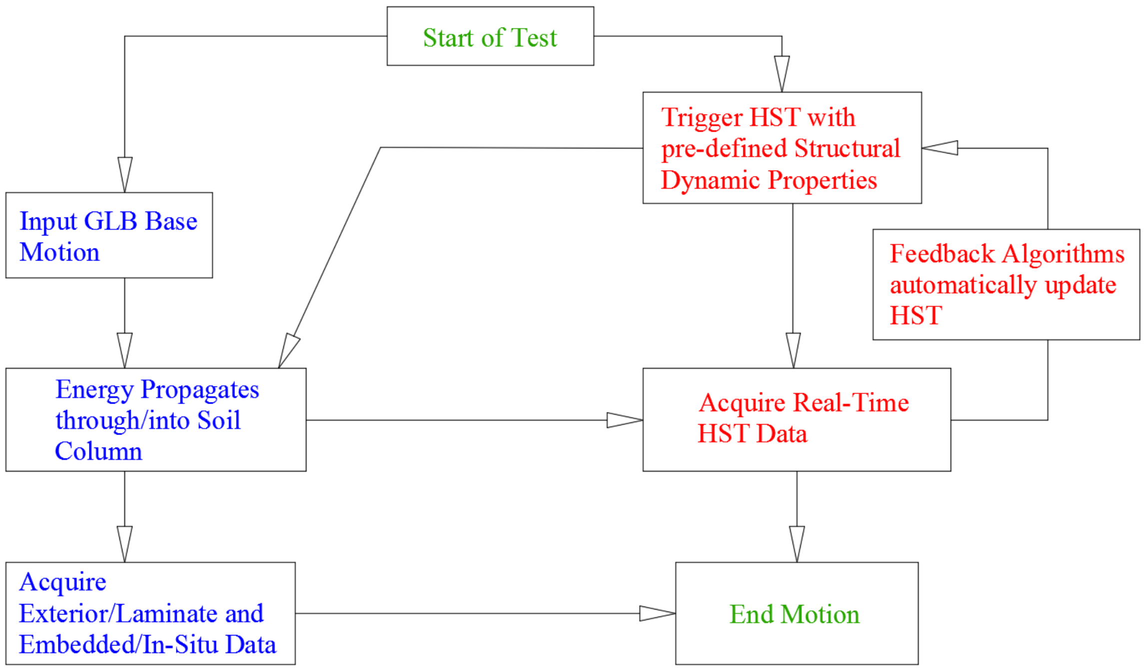

Figure 3 – UB GLB-HST Flow Chart

New GLB-HST Data and Instrumentation

The 2015 and 2016 tests provided a medium for testing new characterization techniques. A full bender-element system has been developed for the GLB. Bender elements (BEs) have been used extensively in geotechnical research at small scales, e.g., triaxial and resonant column setups as well in centrifuges (Brandenberg et al. 2006; Youn et al. 2008; Kim et al. 2017). The goal of the use of BEs in the GLB is to map the state of the model, i.e., shear wave velocity and shear modulus, through the duration of the project. This allows researchers to know the state of the soil before and after each shaking event. The impacts of the shaking can, therefore, be determined for a single motion, series of motions, or for the duration of the experimental program.

Attempts have been made in implementing geophysical techniques. Ground Penetrating Radar (GPR) has been used to try and map the soil structure of the GLB. This system provides information on the density of the soil in the box and identifies any anomalies in the soil system. These new non-destructive techniques provide greater insight into the state of the GLB models after elastic and plastic motions.

The other important change since the SMiRT23 paper is that in this experiment, pore-water pressure transducers (PWPs) and bender elements (BEs) were embedded in the soil. These devices were used to collect in-situ data over the entirety of the hybrid experiment. The data set is comprehensive and cumulatively covers the life of the experiment from model fabrication, i.e., filling of the GLB, all the way through to model disassembly.

The PWPs and BEs are affixed to Measurand ShapeAccelArrays (SAAs), which provide in-situ real-time acceleration, displacement, and temperature data with depth. The SAA devices have been used with GLB models before, e.g., Abdoun et al. (2008). By attaching these devices to the SAAs, the locations of these devices are known at all times, thereby reducing uncertainty in the data obtained. The embedded instrumentation identifies the initial state of the soil and continues to track changes during testing. This information will be used in a corresponding numerical analysis.

ANALYSIS OF EXPERIMENTAL RESULTS

Below is an excerpt of data that illustrates two important factors when considering SFSI. Note that specifics on all of the behaviours observed and theories of what is leading to the changes in response to the GLB-HST model will not be covered herein. The focus of this paper is to provide evidence of the effectiveness of the GLB-HST system via diverse SFSI responses. It should also be noted that the GLB soil column is a plastic medium. Any non-elastic "large" motion, i.e., shear strains larger than fractions of a percent, will irreparably alter the geomatrix on which the HST system sits. Therefore, when conducting these parametric studies, changes in parameters, e.g., GLB base acceleration or HST dynamics, must be conducted carefully so subsequent data can be interpreted as part of the whole. To be specific, the data shown in this section is for three consecutive GLB-HST motions where changes to the overall geomatrix (compared to the total duration of testing) were small and quantified using the aforementioned sensing techniques.

Real-time BE testing and surface inspections help to guarantee that the geomatrix stays within acceptable ranges between individual motions during testing. BE data pertaining to the hybrid experiments will not be analyzed here in this SMiRT paper; however, this data will be available in a future publication.

Ground Acceleration and Pore-Water Pressure Analysis

The factors that lead to ground acceleration, and subsequently to foundation acceleration of sensitive nuclear-facility models, can be best understood by looking at the time-acceleration histories of the GLB-HST setups. As seen below in Figures 4 and 5, the different impedances result in different responses of the GLB-HST setup. These plots show typical laminate acceleration and pore-water pressure responses as functions of changing motion parameters. The acceleration plots describe the motion of the base of the GLB, i.e., source of ground motion, and several soil layers along the height of the soil column. The consecutive data, shown in these plots, was taken at 610-mm (24-in) choice intervals along the height of the GLB. Data for these plots have been shown for the duration of three consecutive GLB-HST motions, all which were less than 10 seconds. Note that for Impedance 1, excess pore-water pressure dominates but laminate (ground) acceleration is lower than Impedance 2 and Impedance 3. For Impedance 3, note that the pore-water pressure generation is least but laminate acceleration is highest.

Slight changes in impedance contribute significantly to the overall shape of the GLB-HST response. For Impedance 1, acceleration is approximately symmetric about the middle cycle of shaking. Additionally, each measurement is nearly in phase and has relatively similar amplitudes. However, Impedance 3 results in a maximum laminate acceleration early in cyclic loading, and then trails off. Impedance 2 shows much higher surficial accelerations.

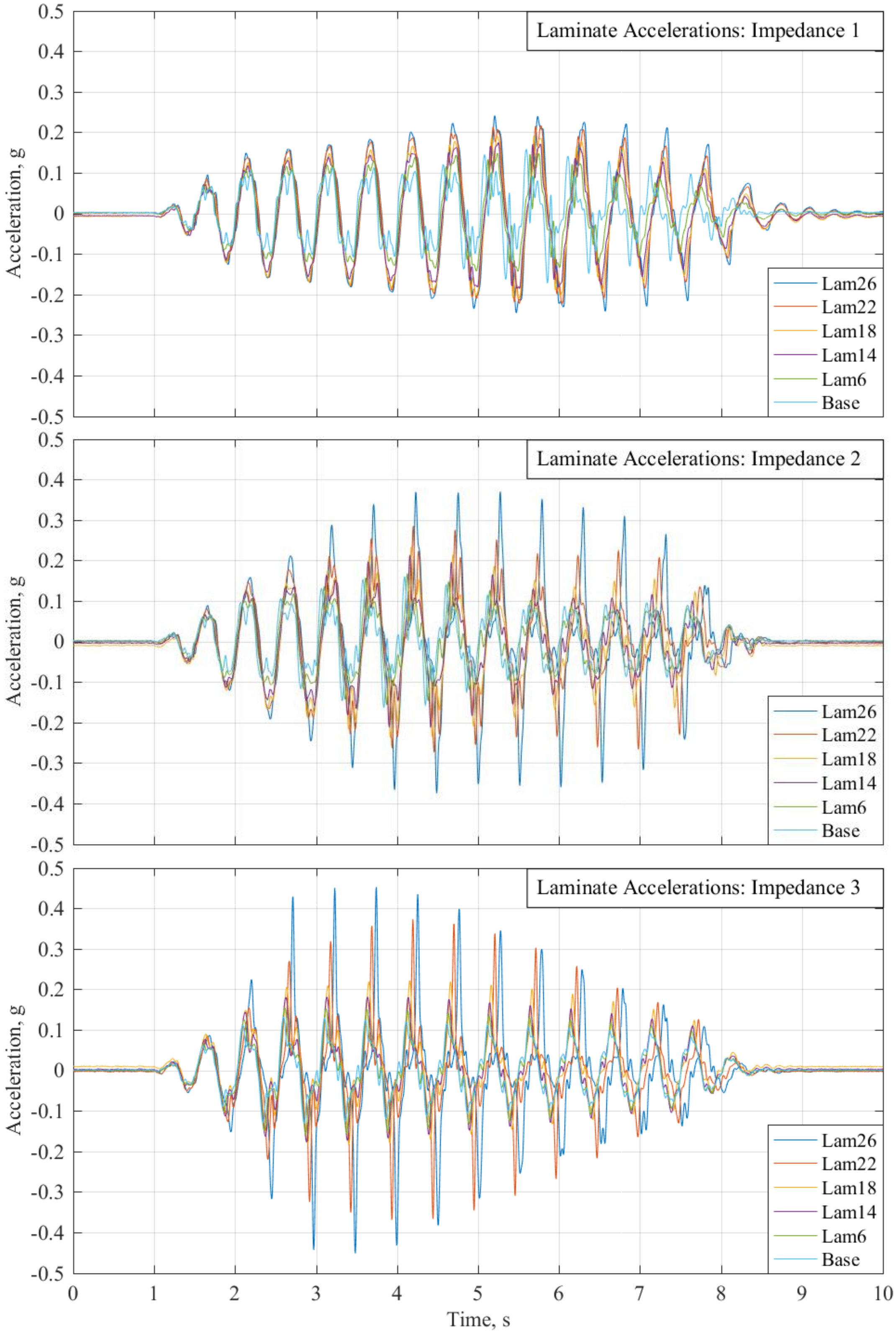

Figure 4 – Laminate Acceleration Response due to Changing GLB-HST Impedances

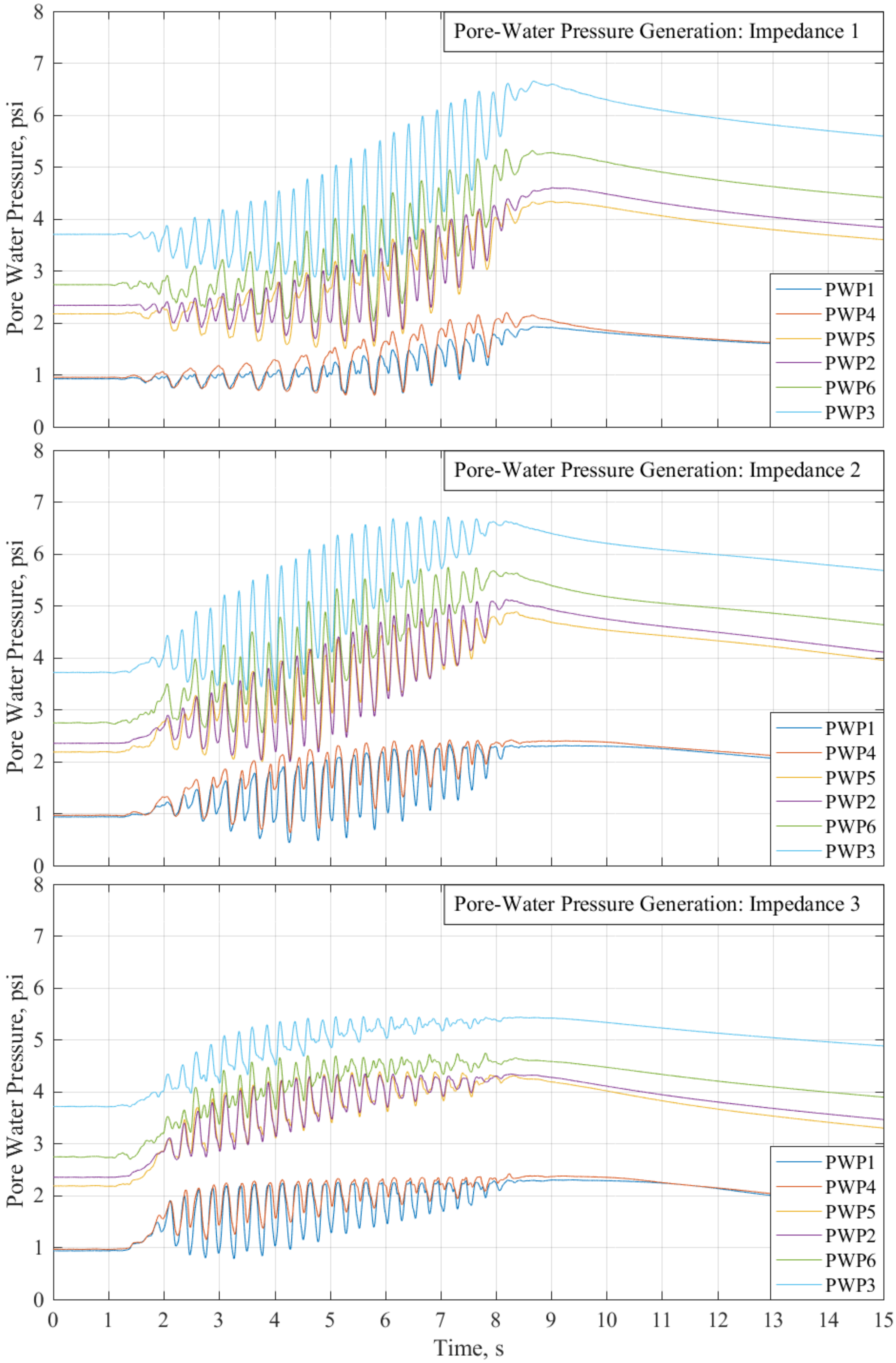

Figure 5 – Corresponding Pore-Water Pressure Response due to Changing GLB- HST Impedances

A simple analysis of the state of the model during shaking can be drawn from looking at the pore-water pressure generation. At static conditions and before any input motion, the GLB model has a hydrostatic pore-water pressure, u_i, at some depth, z. As the model is shaken, pore-water pressure response is measured as the current value, u_f. Terzaghi's equation for effective stress, σ', used here as the simplest of analysis tools, is

$$\sigma' = \sigma - u$$

Ultimate failure can be defined as the point at which the effective stress of the soil reduces to a point in which the soil loses significant shear strength. Assuming a specific gravity and typical void ratio of the GLB Ottawa F-55 material, as measured by Thevanayagam et al. (2003), the total unit weight of the saturated soil is in the approximately 18.8-20.0 kN/m^3 (120-127 lb/ft^3) range. The unit weight of water is 9.81 kN/m^3 (62.4 lb/ft^3). Therefore, failure will occur, with this GLB material, when the excess pore-water pressure, u_f, is close to twice the initial static pressure, u_i.

The plots show that excess pore-water pressure can be a function of the various impedances between the GLB and HST systems. The extended window of data in these PWP plots shows the beginning of excess-PWP dissipation after cyclic loading. PWPs 3 and 6 were embedded in the bottom third, PWPs 2 and 5 in the middle third, and PWPs 1 and 4 in the top third of the soil column. Similar to the acceleration observations, the data obtained from each pore-water-pressure sensor is a function of changes in impedance parameters.

FUTURE RESEARCH AND GOALS

The goal of future research is to isolate and identify the fundamental physics that drive these interactions. Future testing will be performed on representative soils and foundations systems to provide behavioural envelopes that will be used to verify and validate numerical models.

CONCLUSIONS

This paper demonstrated the viability of a methodology to investigate soil-foundation-structure interactions using a real-time dynamic hybrid shaking table in a large geotechnical laminar box. Further, it establishes the importance and uniqueness of hybrid shaking when used in conjunction with large scale testing. The research has yielded comprehensive data, which is still being analysed to determine the factors and specifics that describe the global SFSI response.

New technologies are being used in conjunction with the HST to better characterize the GLB when running experiments. It is important that the state of the soil can be identified at all stages of testing to reduce uncertainty for corresponding numerical analyses. This novel methodology of using hybrid shaking tables in large laminar boxes will provide researchers a better way of determining the critical factors that influence SFSI.

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