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SOIL-FOUNDATION-STRUCTURE INTERACTION INVESTIGATIONS USING HYBRID SIMULATION

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ABSTRACT

Laboratory testing of soil-foundation-structure interaction (SFSI) has proven to be challenging and expensive. Small-scale (1:50 1:70) testing employing geotechnical centrifuges is limited by scale effects and an inability to control dynamic properties of the structure(s). Much larger-scale testing is possible with 1D geotechnical laminar boxes at a small number of laboratories worldwide. Deployment and operation of such boxes is complex. Hybrid simulation offers an added valuable dimension to SFSI testing. The soil-foundation-structure system is partitioned into (a) a physical subsystem: an experimental component representing the soil and foundation, and (b) a virtual subsystem: a computer model of the superstructure, interacting in real-time via actuators, sensors and control systems. Key benefits are (a) foundation models can be tested with multiple virtual superstructures; (b) physical space requirements and costs are reduced; and (c) larger foundation models can be accommodated, minimizing scaling effects. These benefits substantially expand the utility of geotechnical laminar box experiments. In this paper, we describe proof-of-concept tests that we performed to demonstrate viability of SFSI hybrid simulation, and present measurements that (i) elucidate the role of superstructure dynamics in foundation response, and (ii) can be used to validating computational SFSI models. The physical subsystem was a 10-ft deep pile-group foundation model in a 23-ft laminar box filled with saturated sand. One dimensional seismic excitation was applied at the base of the laminar box to represent bedrock input at depth. Interface conditions representative of different superstructures were applied to the foundation using a second shake table.

INTRODUCTION

The purpose of the experiment presented in this paper is to investigate the procedure and challenges related to hybrid simulation of soil-foundation-structure interaction (SFSI). It is the first step towards understanding this complex phenomenon and provides direction for the hybrid experiments to follow. In particular, it suggests the important role played by superstructure dynamics in the response of the soil, foundation and pore water response.

Hybrid simulation is an experimental method used to study the dynamic response of complex engineering systems [1, 2, 3, 4]. It involves the combination of two systems, a physical and a computational subsystem interacting with each other. The interaction between the two subsystems is accomplished by means of actuators and/or shake tables, which apply the interface conditions between the physical and the virtual subsystems. It can be broadly divided into two categories: pseudo-dynamic and dynamic hybrid simulation. In the commonly used pseudo-dynamic form of hybrid simulation, the inertial effects of the physical subsystem are taken into account in the numerical subsystem, usually as lumped masses. In dynamic hybrid simulation, the inertial effects are part of the physical subsystem and hence, this method should be used when the physical subsystems of interest cannot be represented using a simplified approach. Clearly, dynamic hybrid simulation is the appropriate technique to study complex interaction phenomena, such as the soil-foundation-structure interaction described above. One of the most important benefits of the hybrid SFSI simulation approach is the fact that the properties of the superstructure can be easily changed by simply altering the computer model. As a result different superstructures can be emulated and the response in each case can be evaluated using the same experimental setup. For this purpose, an innovative impedance matching control approach can be used so that the stability and robustness of the simulation can be ensured. More specifically, the impedance of the actuator used to apply the interface conditions is matched to the impedance of the emulated superstructure.

Preliminary experiments performed in the Structural Engineering and Earthquake Laboratory (SEESL) at the University at Buffalo provide information on this complex phenomenon. More importantly, they provide useful experience, not only in the design and the construction of the experiment but also in the details on the challenges related to this type of experiments. This work is driven by the need for sufficiently rich experimental data to evaluate numerical models of complete soil-foundation-structure systems. There are clear practical impediments to performing such system-level experiments at full-scale. Various approaches have been taken to study SFSI experimentally.

Centrifuge modelling: Centrifuge modelling has a long history in geotechnical engineering [5, 6], stemming from the additional scaling degree-of-freedom resulting in proper stress levels in the soil. Centrifuge modeling has been used to study shallow foundations and deep foundations [7, 8, 9] subjected to earthquake shaking. Realistic superstructure models are rarely incorporated in centrifuge models. In a few cases, a cantilevered mass or tower structure is used. Recently, simple frame superstructure models have also been used [10, 11,12]. Although the type of hybrid simulation technology described herein may become possible in the context of centrifuge testing, such technology for centrifuge testing has not yet been developed to study full SFSI at the system-level.

Role of superstructure in soil-foundation response: Even with simple superstructure models, centrifuge tests provide evidence that the superstructure has a considerable influence on the behavior of the soil-foundation system. For example, Madabhushi [13] observed that in saturated soil, effective frequency shift resulting from soil plastification depends on the initial frequency of the combined soil-foundation-superstructure system relative to the predominant earthquake frequency. Madabhushi [14] also observed that the superstructure dynamics influences liquefaction-induced failure mechanisms. Pak and Ashlock [15] noted that the extent to which a uniform equivalent shear modulus can be used to model dry sand beneath a foundation depends significantly on the superstructure. These findings highlight the need to use a variety of superstructure models to obtain comprehensive system-level data.

1-g laboratory and field experiments: There have also been a number of SFSI experiments in the 1g environment using shake tables and soil boxes [16, 17, 18, 19, 20]. Such tests are also restricted to simple tower-like superstructures due to laboratory space and other limitations. Furthermore, testing with a different superstructure would imply fabricating a new model, leading to additional time and cost. Field experiments have also been carried out to characterize SFSI using ambient and force vibration experiments [21, 22]. Data from such tests have to be limited to low-level excitations. Furthermore, it is difficult to obtain detailed information about the soil-foundation response in the field.

Role of hybrid simulation: While it may not be possible by any simple approach to test complete soil-foundation-structure systems at full scale, hybrid simulation offers potential for a very good approximation to such a test, by systematically coupling subsystems. It allows adaptability by allowing a physical soil-foundation system to be coupled with multiple complex virtual superstructure models. We note that an early NEES project [23] utilized all of the above approaches separately to study the SFSI problem. Hybrid simulation adds an extra dimension by integrating many of these approaches enabling a fully coupled simulation as shown in Figure 1.

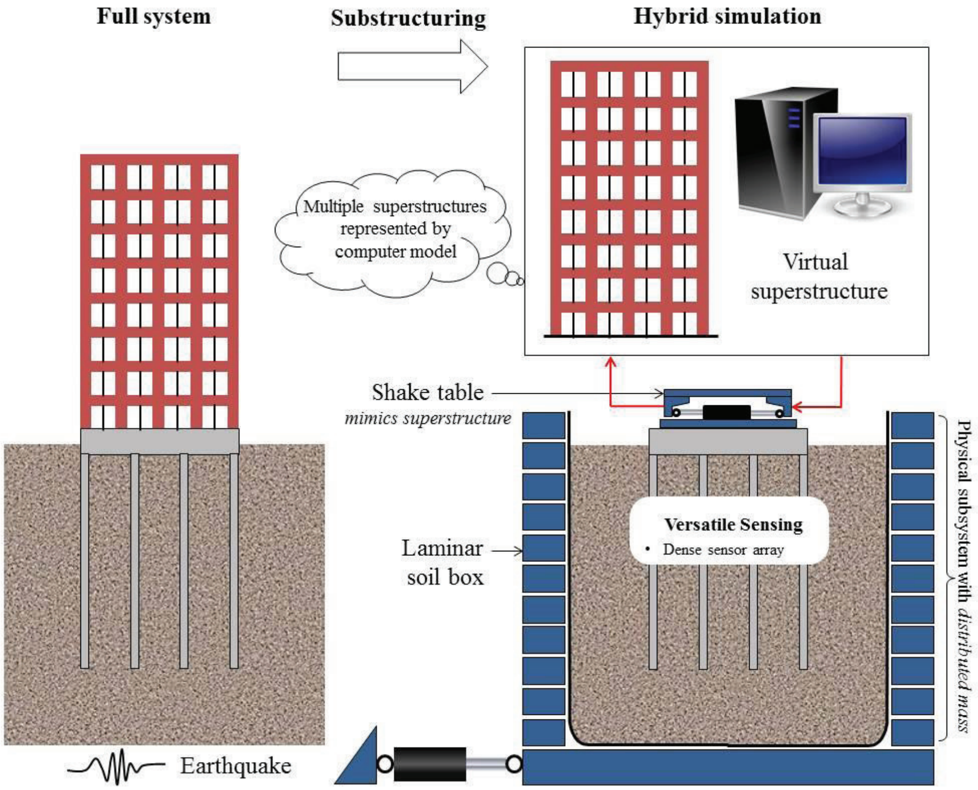

Figure 1. Schematic of hybrid SFSI simulation concept

HYBRID SOIL-FOUNDATION-STRUCTURE INTERACTION (SFSI) SIMULATION

In the experiment described here, the physical substructure of interest is the soil-foundation system and the superstructure is represented by a small shake table applying the interface conditions. The physical subsystem is a pile foundation system built in saturated soil contained in a large-scale geotechnical laminar box. The total height of the laminar box is approximately 23ft and the saturated soil was 15.5ft high. The shake table used to apply the interface conditions was designed to have a small footprint specifically for dynamic hybrid simulation applications. The actuator in this shake table is located under the platform resulting in a small and symmetric configuration. Figure 2 shows the experimental setup in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo. In order to isolate variables of interest, instead of using active feedback for the interface conditions, we represent the superstructure impedance by varying the amplitude and phase offset of the interface shake table. Employing active feedback is the next logical step, and is a focus of our current work.

Experimental setup

The foundation consisted of six 10.5ft long schedule 80 steel pipes of 1 inch nominal diameter. To ensure the necessary pile axial capacity, a cone penetration test (CPT) was conducted prior to their installation. The final configuration after all six piles were driven into the soil, is shown in Figure 3a. After the placement of the piles, steel plates were attached to the piles to provide support for the shake table. This allowed for errors in the positions of the piles. The final configuration is shown in Figure 3b.

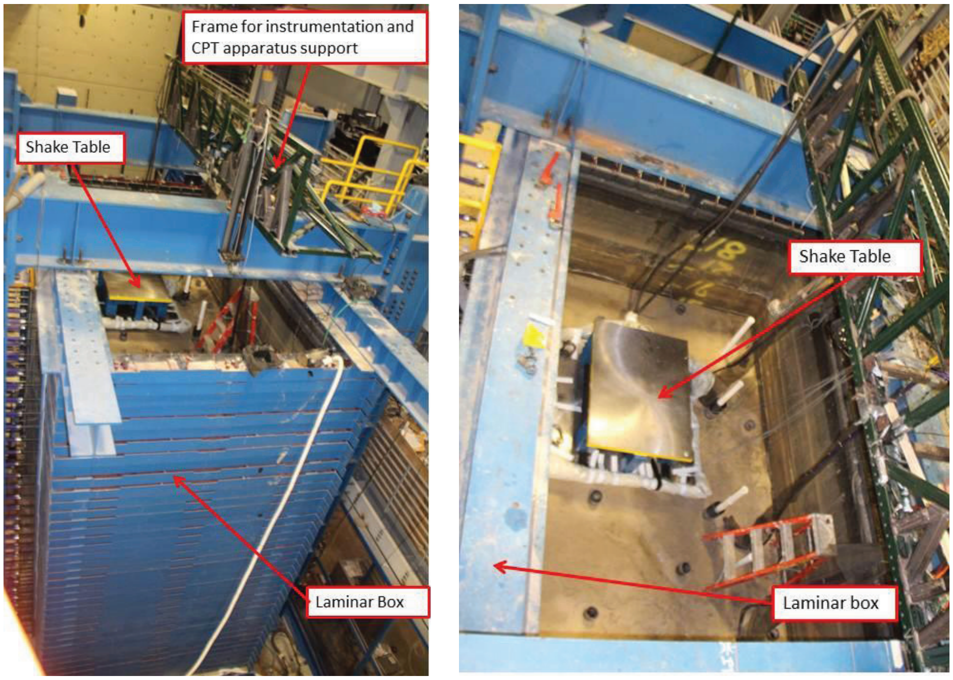

Figure 2. General view of the experimental setup

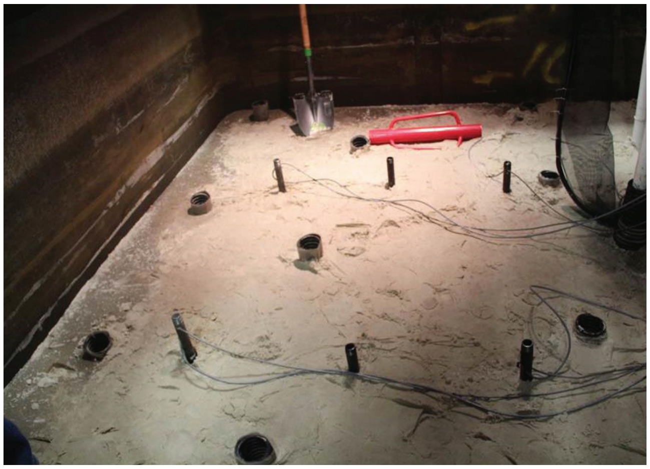

Figure 3a. Pile foundation installed

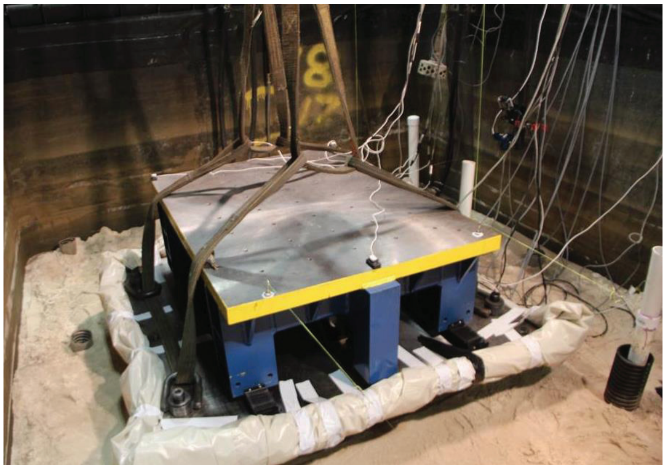

Figure 3b. Shake table mounted on piles

Instrumentation

The four corner piles were instrumented with strain gauges and triaxial accelerometers by embedding these sensors in couplers in the piles as shown in Figure 4. These sensors were carefully waterproofed. The laminar box itself was equipped with string potentiometers at the level of each laminate as well as accelerometers in both horizontal directions. Pore pressure transducers were embedded in the soil to track pore water pressure at different depths.

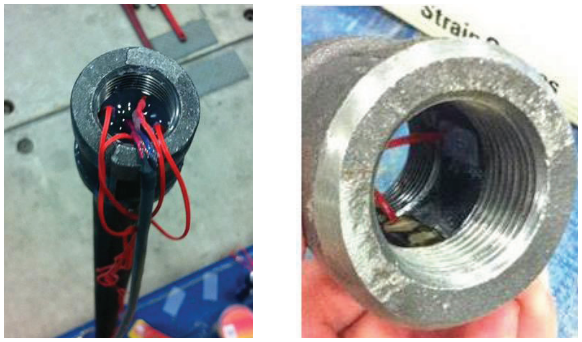

Figure 4. Inside view of instrumented coupler

The shake table representing the superstructure was also equipped with instruments to measure its response during the earthquake shaking. Accelerometers were used in all three directions and string potentiometers were positioned to capture the displacement, rotation, torsion and settlement of the table. The sensors used to measure the shake table's response are shown in Figure 6.

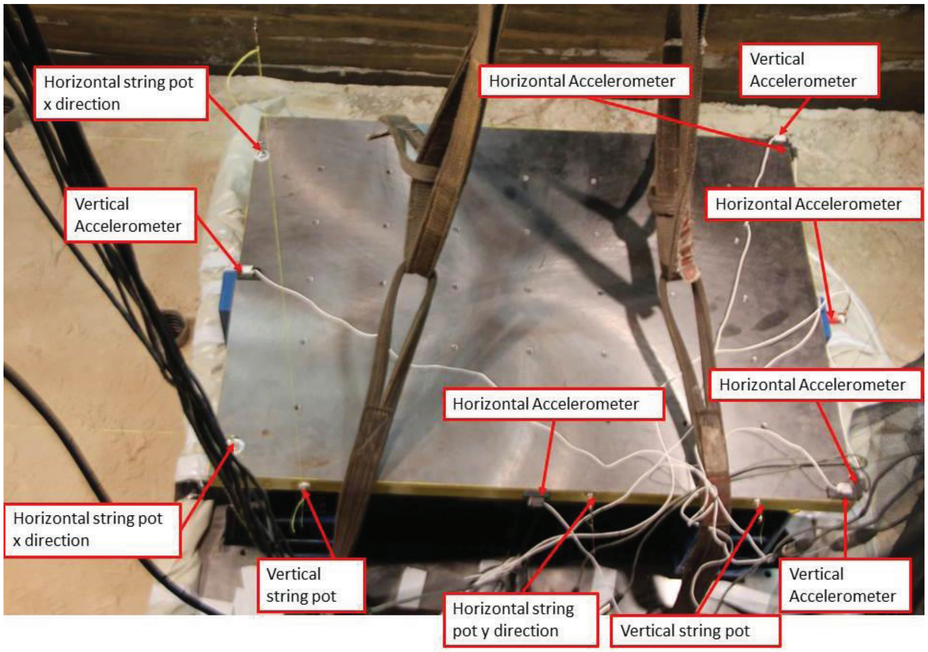

Figure 6. Shake table instrumentation

The shake table was equipped with additional sensors, including two load cells measuring the applied force. The differential pressure, ΔP, in the actuator's chambers was also measured, providing information the hydraulics and the forces applied on the shake table.

Experimental protocol

Experiments were driven by harmonic input at the base of the laminar box. To represent different superstructures at steady state, the shake table atop the foundation was driven with the same frequency but at different amplitudes and phase offsets relative to the laminar box excitation. Additional experiments were conducted for which there was only input at the base of the laminar box without applying any interface conditions through the shake table, which is equivalent to having a rigid superstructure. The amplitude of excitation was gradually increased through several experiments to a maximum of 0.2g, which corresponded to 0.12in displacement at the base of the laminar box. Prior to each experiment, free vibration tests were performed to obtain the frequency of the system and to assess how the state of the soil-foundation system evolved over the course of the experiments.

ANALYSIS AND INTERPRETATION

Experiments were performed parametrically via gradual variation of the shaking input and the superstructure properties. The response of the system during each experiment was captured using the aforementioned sensors and testing protocol. Analysis of the data produced meaningful information through inter-test comparisons. For example, for the same base input excitation, the effect of different superstructures is isolated and identified. The results show that the response of the system varied significantly while changing the superstructure parameters.

Figures 7 to 11 show comparisons of three different cases: (a) rigid superstructure, for which harmonic excitation was applied to the base of the laminar box and no input was applied to the shake table, (b) harmonic base excitation and a superstructure with natural frequency less than 3Hz (superstructure 1), and (c) harmonic base excitation and a superstructure with natural frequency more than 3Hz (superstructure 2). Data illustrated in the following figures were obtained for harmonic excitation of 3Hz frequency and 0.1g input acceleration, which corresponds to displacement of 0.11in, at the base of the laminar box. The input to the shake table was also sinusoidal with 3Hz frequency and 0.8in amplitude.

Acceleration was measured at both the shake table and at a location approximately 3ft deep in the saturated soil. Comparisons of the measured accelerations for the different superstructures are shown in Figures 7 and 8. The embedded pore pressure transducers captured the change in the excess pore water pressure during the experiments, as shown in Figure 9. Strains were recorded at the level of the instrumented coupler (Figure 10) and the settlements of the shake table are shown in Figure 11 for the three subsequent tests. Figure 12 shows the change in natural frequency during the progression of the experiments, which gradually decreased until it reached approximately 4Hz, after which no significant change was observed. The settlement progression for all consecutive experiments is presented in Figure 13. The magnitude of the shake table settlement reached a limit value of 0.6in and was measured at two points (east and west side) of the platform. Significant settlement was only observed in trials containing strong ground motions. In order to investigate the liquefaction potential for different superstructures, the cyclic stress ratio (CSR) was calculated from the obtained experimental data [24] using the following equation:

$$\mathrm{CSR} = \frac{\tau_{\mathrm{cyc}}}{\sigma_{\mathrm{vo}}{}'} = 0.65 \cdot \mathrm{a}_{\mathrm{max}} \frac{\sigma_{\mathrm{vo}}}{\sigma_{\mathrm{vo}}{}'} \left(\frac{\mathrm{W_L} + \mathrm{W_S}}{\mathrm{W_S}}\right)$$

Where a_{max} is the maximum acceleration of each soil layer and σ_{vo} and $\sigma_{vo}{}'$ are the total overburden pressure and the initial effective overburden pressure on sand layer under consideration respectively. The CSR value was then multiplied by the ratio of the sum of the weight of the laminar box laminate and the weight of the soil of the specific layer over the weight of the soil. The soil properties used in this calculation were obtained from a combination of CPT testing and utilizing empirical relationships developed from previous testing in the laminar box. For the specific soil properties and number of testing cycles, the onset of liquefaction will occur at CSR values of 0.2. Figure 14 shows the different CSR values for three different superstructures. The case of the rigid superstructure provides a base case for comparison. Conventional design methodologies often neglect SFSI as they consider it to be beneficial or negligible in terms of energy dissipation; therefore ignoring it is conservative [25]. However this approach does not account for the full behaviour of the multiphase system. In the case of superstructure 1, the CSR in the upper layer of the soil reaches the 0.2 limit, indicating that liquefaction has occurred and that excitation past this point would result in catastrophic failure. Furthermore, the accelerograms (Figures 7 and 8) recorded in both the soil and at the table for this trial shows a higher peak acceleration compared to the rigid case. The case of superstructure 2 exhibits an equally interesting response including a higher CSR and acceleration at the shake table. The acceleration recorded in 3ft into the soil is much less in this case, however, highlighting the nonlinearity associated with SFSI. These results show that SFSI has a significant impact on the behaviour of the system and that it cannot be neglected due to the complex boundary conditions and limit states involved.

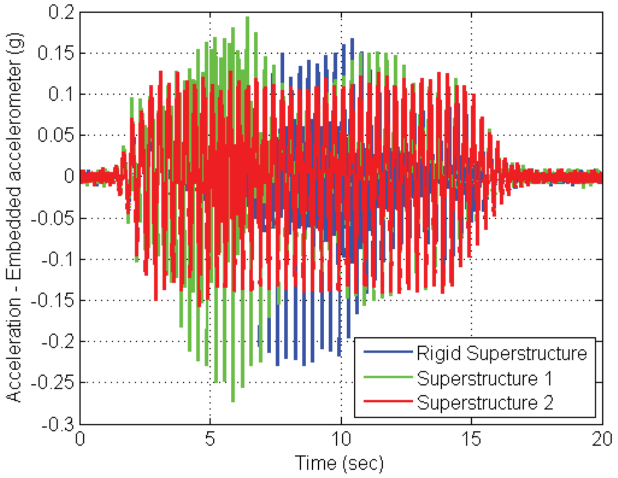

Figure 7. Acceleration from embedded accelerometer at 3ft depth

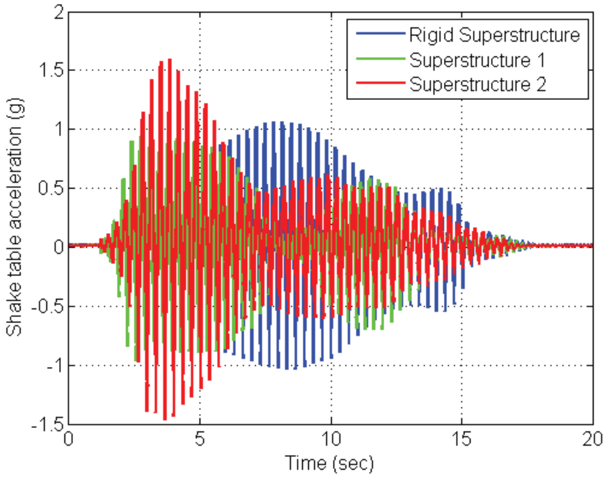

Figure 8. Shake table acceleration

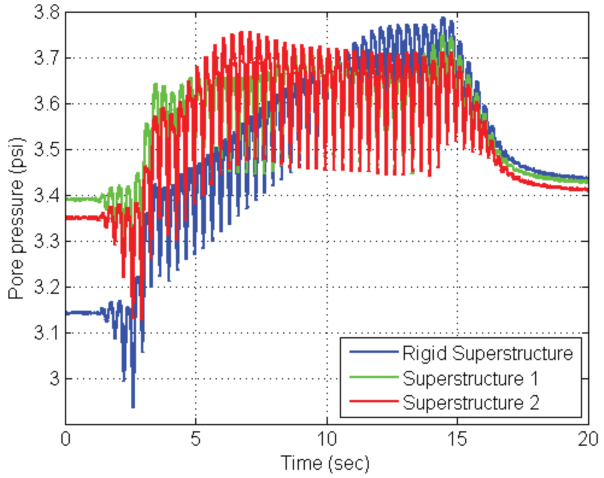

Figure 9. Pore pressures at 10ft depth

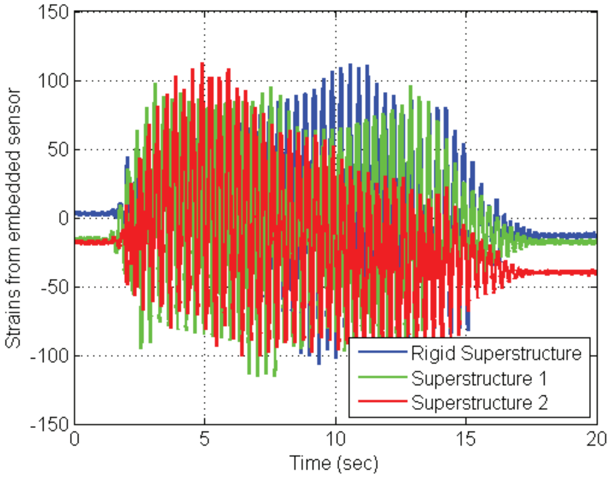

Figure 10. Strains from embedded sensor at 3ft depth

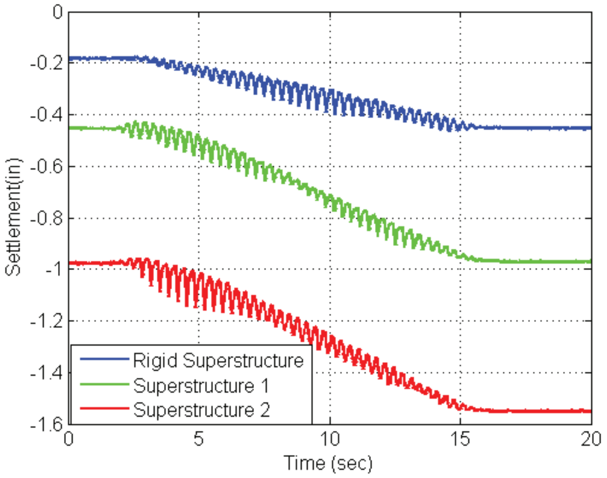

Figure 11. Shake table settlement

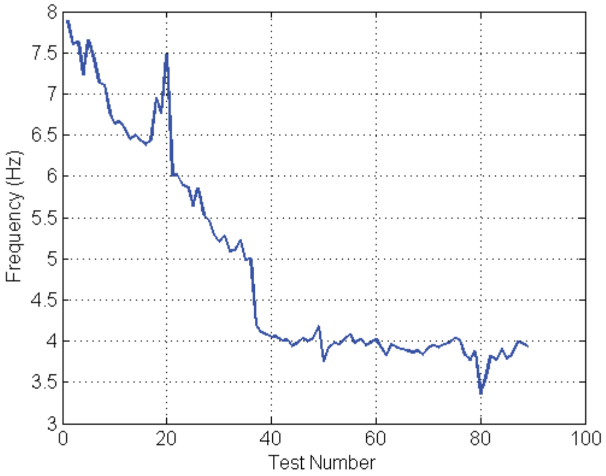

Figure 12. Frequency changes during testing

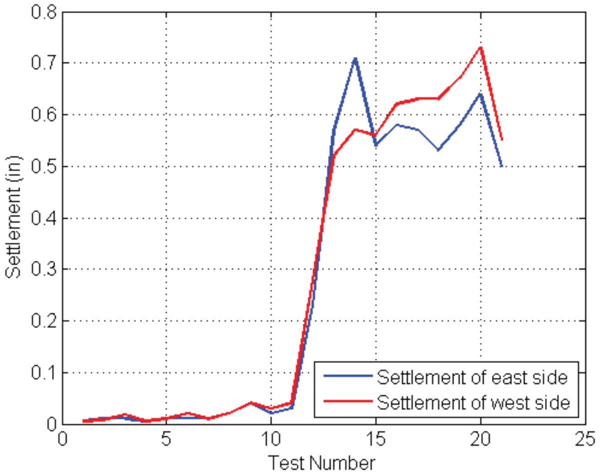

Figure 13. Settlement progression during testing

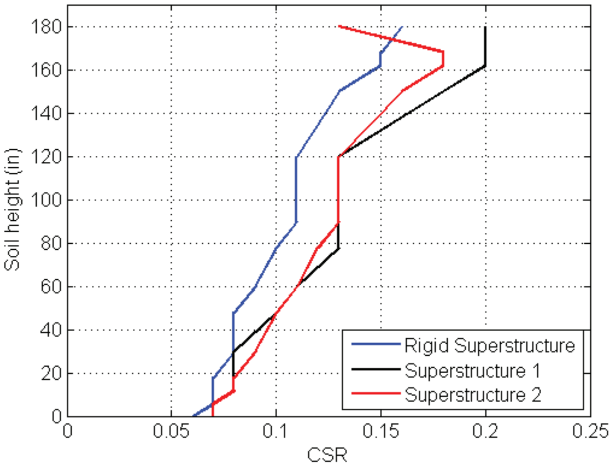

Figure 14. CSR values for consecutive tests

FUTURE RESEARCH AND GOALS

We have shown that hybrid simulation of soil-foundation-superstructure interaction is viable and that interaction with the superstructure can significantly influence soil-foundation response. Active control of the interface will enable more realistic representation of superstructure dynamics and quantification of the effect of interaction under transient conditions. This will lead to a better understanding of the mechanics that drive critical SFSI scenarios.

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