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LARGE SCALE SOIL-STRUCTURE-INTERACTION TESTING OF PARTIALLY BURIED STRUCTURES

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ABSTRACT

Most small modular reactor (SMR) designs that are currently under development, including several of the current generation (Gen III+) and the entire next generation (Gen IV) nuclear power plant (NPP) designs, place the critical compartments (e.g., reactor containment) or the entire structure below ground level. This structural layout is advantageous in protecting critical compartments of NPPs from natural and man-made external hazards; however, partially or fully burying these structures cause potential uncertainties related to the performance against earthquakes where soil-structure-interaction (SSI) is expected to have a significant impact on the structural response. This study presents the design and results from unique large-scale soil-structure interaction experiments. A buried caisson is subjected to a series of combined vertical and horizontal loads to provide insight into the fundamental behavior of buried/semi-buried structures. The experiments will aid in: (i) validation of nonlinear constitutive material and interface models, (ii) measuring dynamic capacity of soil-structure assemblies, and (iii) development of models for computing capacity and permanent deformations. The outcomes from this research will provide data on large-scale SSI experiments to validate numerical models with the overall goal of highlighting the importance of SSI on the seismic response of SMR designs while accounting for their distinct features in a generic manner and providing technical basis for improved regulatory oversight for enhanced safety.

INTRODUCTION

A brief survey gathered from publicly available documents pertaining to the structural features of next-generation nuclear power plants (NPP), including small modular reactors (SMRs), have a common attribute of having partially or fully buried structural compartments. Partially or fully burying these structures cause potential uncertainties related to the performance against earthquakes, where soil-structure-interaction (SSI) and soil-structure interface behavior are expected to impact the structural response significantly. One of the major challenges of using nonlinear analysis methods for soil-structure-interaction problems is the dependence on reliable and representative interface models that are experimentally validated. Currently, this validation relies primarily on small-scale laboratory tests [1], but it is unclear if these tests capture the stress states and failure modes relevant to the buried compartments of SMRs. The lack of large-scale SSI testing is mainly credited to the challenge of conducting tests where the structure and soil deposits are representative of realistic field conditions. One of the few large-scale tests was conducted in the TRISEE project [2] by simulating the SSI behavior of a shallow foundation in a large concrete sandbox with a mix sand. The tests provided valuable experimental data but had major limitations due to having the test caisson in close proximity to the sandbox boundaries. Therefore, additional large-scale testing is needed to understand the nonlinear behavior and validate numerical models to advance the current industry practice in conducting SSI analysis of nuclear power plants (NPP).

EXPERIMENTAL PROGRAM

This study describes large-scale SSI tests performed at Auburn University's Advanced Structural Engineering Laboratory (ASEL). One of the unique features of the laboratory is including a 24 ft long, 10 ft wide, and 20 ft deep geotechnical testing chamber within the strong floor, which is used to conduct the SSI testing (Fig. 1). The tests will explore the response of both circular and cuboid caissons to combined vertical and horizontal loads using surface actuators (Fig. 2). Instrumentation will be placed at varying distances from the caisson to monitor the interaction of the caisson movements and the behavior of the surrounding soil (Fig. 2), and pressure transducers will be placed on the surface of the caisson to monitor the interface behavior. The major parameters for the testing will be: (i) shape of the test caisson (circular and cuboid), (ii) exterior surface type (steel, concrete, geosynthetic), and (iii) soil saturation level to investigate the influence of water table elevation, and (iv) over-pressurization level.

Figure 1. Geotechnical chamber at Advanced Structural Engineering Laboratory of Auburn University

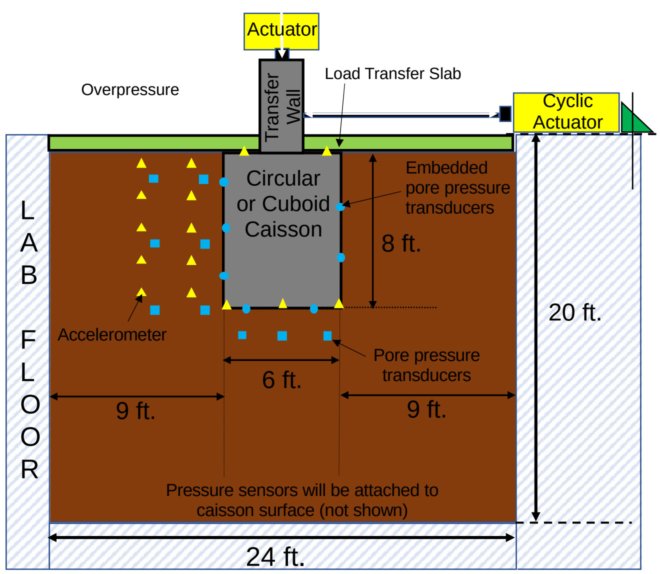

Figure 2. Schematic view of soil-structure-interaction experiments

The experimental results will be used for: (i) validation of nonlinear constitutive material and interface models, (ii) measuring dynamic capacity of soil-structure assemblies, and (iii) development of models for computing capacity and permanent deformations. The experimental program is currently being developed, and this presentation will share insights from early tests and describe plans for future experiments.

Benchmark Numerical Model Development and Test Caisson Preliminary Design

In order to design the test caissons, loading apparatus, and load transfer fixtures, it is critical to have estimations on the caisson response under lateral loading at target embedment levels. To accomplish this, tests available in the literature on lateral response of piers were reviewed, and studies having piles with similar aspect ratios (pile embedment-to-diameter ratio) were selected for evaluations using numerical analysis tools considered for this study. Each analysis tool was used for validating experimental research, and the analysis tool with better predictions of the experimental lateral load-displacement response of the piers was selected for further evaluation of the caissons that are expected to be tested in this research.

Two numerical analysis tools were used to obtain estimates of the static lateral strength and stiffness of tested piers. The first software used in the analysis was FB-MultiPier, which couples nonlinear structural finite element analysis with nonlinear static soil spring models to predict the lateral response of foundation systems. The second software used for the studies was FLAC3D, a continuum-based numerical analysis software commonly used for geotechnical analyses. Both software were used to predict the piers tested by Wang et al. (2022) [3]. Where the study included a total of four tests using two steel monopiles with different diameters (0.9 ft. and 1.5 ft. [0.273m and 0.457m]) at two different burial depths (3.28 ft. and 4.92ft. [1.0m and 1.5m]). The four piers tested in this research had aspect ratios corresponding to 3.66, 5.49, 2.19, and 3.28, respectively. The four load-displacement responses reported from the study were compared with the results obtained from the two numerical analyses to validate the modeling approach. Comparisons made against the test data indicated reasonably well predictions obtained using both software, as shown in Figure 3. FB-MultiPier results overpredicted the strength while underpredicting the initial stiffness. On the other hand, the results obtained by FLAC exhibited overprediction of the stiffness but underpredicted the ultimate resistances.

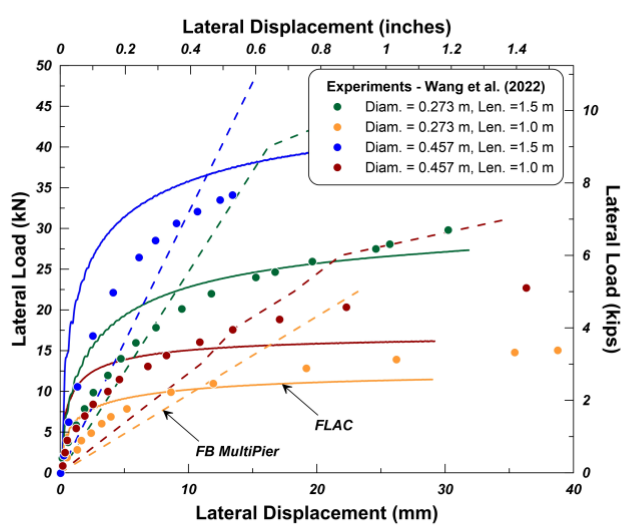

Figure 3. Comparisons of experimental lateral force vs. displacement responses against numerical analysis results

Further evaluations were conducted using FB-MultiPier, which provided more accurate comparisons and upper-bound strength predictions against the experimental results. Bending moment measurements reported along the length of the piers, calculated using strain gauge measurements on the piers, were compared against the ones obtained from the analysis results. The moment variation curves in Figure 4 indicated reasonable comparisons between the test and analysis results. The comparisons also demonstrated that the modeling approach was applicable for low aspect ratio piers also considered for the caisson study. Using a similar modeling approach developed using FB-MultiPier, additional predictions were obtained for the caisson size and burial depth combinations considered for this study. The analysis included a 3 ft. diameter caisson with aspect ratios of 1.0, 2.0, 3.0, and 4.0 (corresponding to 3 ft., 6 ft., 9 ft., and 12 ft.). The responses obtained from the study for different aspect ratios are shown in Figure 5. These results will be used to design the caisson and test fixtures to apply the necessary load without overstressing the test specimens or fixtures.

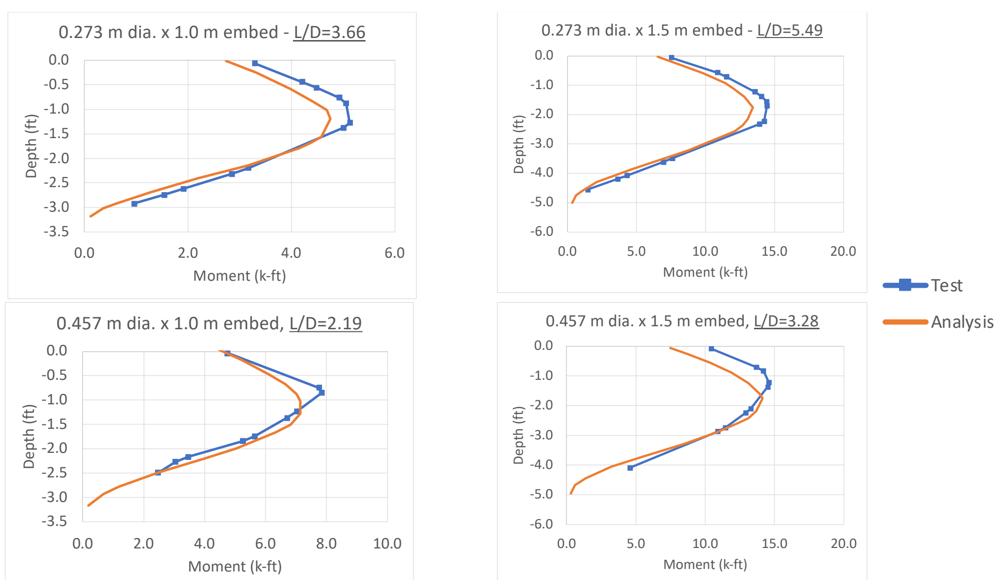

Figure 4. Comparisons of moment variations along the length of tested piers against analysis results

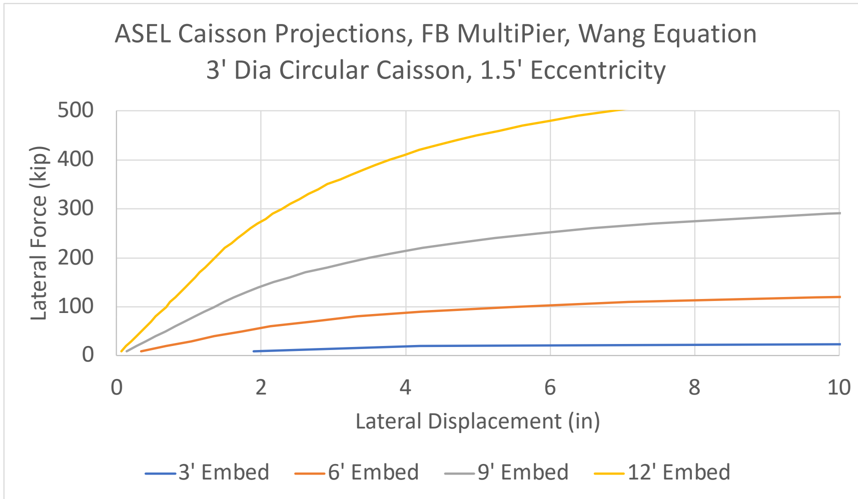

Figure 5. Lateral force vs. displacement response predictions for caisson specimens

CONCLUSION

This research will conduct large-scale tests of buried structures to generate the data needed to characterize the soil-structure interface behavior (e.g., friction, sliding, gapping, uplift, rocking effects) and soil plasticity behavior under dynamic loading at large scale. The tests will generate fundamental parameters for developing a reliable SSI analysis framework. The primary goal of this project will be to highlight the importance of SSI on the seismic response of SMRs while accounting for their distinct design features and providing technical basis for improved regulatory oversight for enhanced safety. This presentation will include preliminary results from the ongoing experimental program and provide insights into the following studies for developing a framework for SSI investigations of partially buried SMRs.

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