International Research (Project No.:2019W-03)

Project name: Seismic Soil-Foundation-Structure Interaction in Unsaturated Soils
Principal Investigator: Majid Ghayoomi
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Research period: June 1, 2019 ~ March 31, 2021
Research location: Disaster Prevention Research Institute and University of New Hampshire
Number of participants in the collaborative research: 4 (DPRI staff: 2 , non-DPRI staff: 2)
- Number of graduate students: 1 (Master students: N/A, Doctor students: 1) (Included number)
- Participation role of graduate students:
[Performing the experiments including centrifuge tests, running the data analyses, and writing papers and publications]

Implementation status in FY2019:

The project investigated the effects of unsaturated soils on seismic response of soil-foundation-structure systems. Soil-Foundation-Structure Interaction (SFSI) evaluates the collective seismic response of a system containing the superstructure, foundation, and surrounding soil given the earthquake motion at the ground surface. For SFSI analysis, regardless of the approach, surrounding soil plays a critical role, as it impacts both the site response and the motion transferred to the foundation. Recent studies on foundation rocking have highlighted the potential benefits of allowing inelastic foundation response during earthquake loading. For example, in "foundation isolation" design, the foundation is purposefully under-designed to promote soil yielding at the foundation-soil interface, shifting the inertial forces and ductility demand away from the superstructure. In a conventional design, strength mobilization at the foundation level is restricted and plastic deformation is isolated to above-ground structural members.

The behavior of unsaturated soil is complex and differs from dry and saturated soil deposits, because inter-particle suction stresses increase the effective stress and change the dynamic characteristics of soils. Despite the proven significant effects of degree of saturation on dynamic soil properties, current practice relies on procedures that do not directly include partially saturated soil conditions at system level; especially considering the seasonal and climatic-driven fluctuation of water table. Consequently, this uncertainty would be extremely critical in improving SFSI analysis procedures. Although rocking foundations may improve margins of safety and reduce retrofitting costs once a structure is subjected to an earthquake, the designs come at the cost of increased settlements and rotations at the footing level. Thus, the impact of degree of saturation on soil stiffness and damping should be considered in evaluating the performance of rocking isolated structures, especially because stiffer unsaturated soils would reduce the seismic settlement.

In FY19, a series of dynamic centrifuge tests were performed to investigate the performance of a slender single-degree-of-freedom rocking shallow foundation embedded in sandy silt with varying groundwater table conditions. The tests included six successful target tests (dry, saturated, and partly saturated) out of ten trials and calibration tests. The structure and soil layer were heavily instrumented to capture different aspects of the response of the soil-foundation-structure system; schematically shown in Figure 1. In partly saturated tests, water level was lowered from the soil surface by adjusting the drainage valves at the bottom of the laminar container and monitoring the pore pressure profile. Results from these tests can be interpreted through the far-field response of the soil layer, kinematic and inertial effects, settlements, rocking effects at the footing level, soil stiffness and damping properties, and lateral earth pressure. The data suggested that as the depth of the groundwater level increased the settlement at the center of the structure decreased, regardless of input motion intensity. Also, by increasing the depth of the water level, the cumulative residual rotations decreased. Therefore, the importance of considering water table fluctuation in rocking isolated designs is important while lowering the water table elevation may reduce the foundation deformations when compared to both fully saturated and dry conditions.

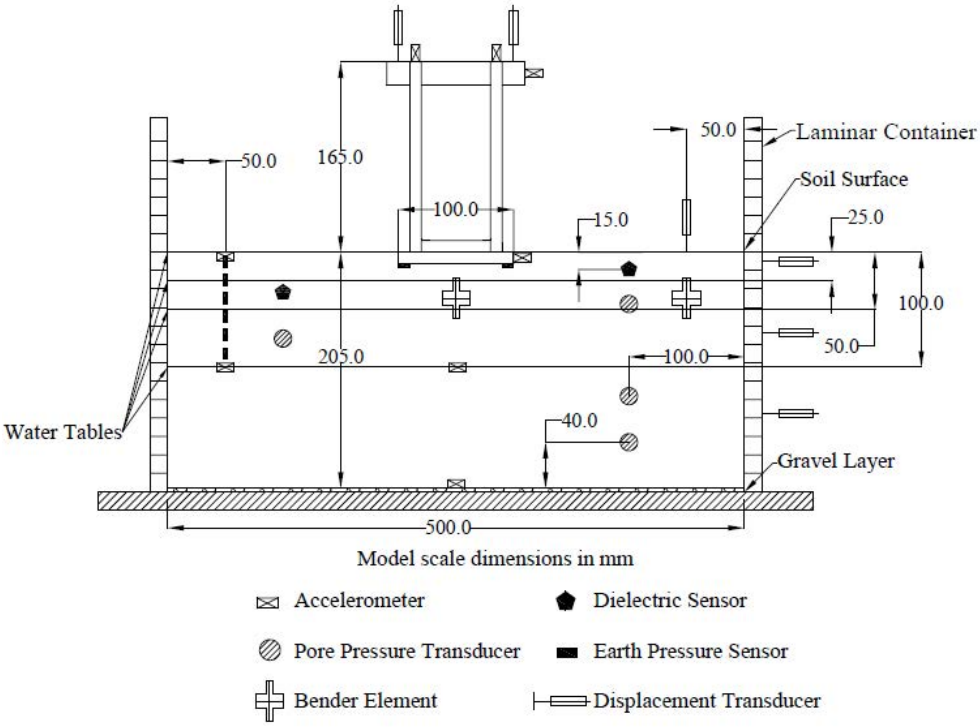

Figure 1: Schematic and instrumentation layout of a typical centrifuge experiment in this research.

Implementation plan in FY2020

Given the complex nature of soil-foundation-structure interaction systems and to better understand the contrast in yielding soil-foundation versus yielding structure, the next series of centrifuge experiments will investigate the performance of a more conventionally designed structure placed on variably saturated soil conditions. The system will encapsulate structural fuses at the column base connections to isolate and guide the weak plastic sections. At these locations, the cross-sectional area of the columns is reduced based on the expected yield strength of the fabrication material and the predicted spectral acceleration at the soil surface determined for the fixed-base natural period of the structure. The structural fuses will be instrumented with strain gauges on opposite sides of the bending faces in order to estimate axial and flexural demands at each location. The soil material, preparation technique, and input earthquake motions used in these tests will be the same as those used for the rocking isolated experiments. Additionally, the water table elevations will also be roughly equivalent to the ones in the previous set of tests. The structural design for these tests can be seen in Figure 2(a) and (b). To facilitate comparisons of experimental results between the rocking isolated and conventionally designed structure, the overall dimensions and bearing pressure are designed to be about the same.

Results from the experiments on unsaturated soil cases (i.e., soil layers with water table below the ground surface) will be directly compared with the results from the fully saturated and dry conditions. In addition, these results will be compared with their counterpart in rocking foundation isolated structures with similar saturation condition. It is hypothesized that the unsaturated soil may amplify accelerations and forces on the superstructure by increasing the stiffness and reducing the damping of the underlying soil compared to the saturated and dry soil conditions. This may result in increased inelastic deformations and flexural drifts compared to the saturated and dry soil. However, the extent of these effects will depend on the depth of the water level. The amount of rotation experienced at the foundation level will be a function of the nonlinearity and flexural drifts experienced by the superstructure, which may cause increased inertial interaction. If a high structural nonlinearity is achieved, then the amount of rotation should be increased. In such a condition the increased accelerations at the superstructure level in unsaturated soil layers may cause the residual rotations at the foundation level to be increased compared to the saturated and dry soil conditions. However, the overall settlement of the structure in the fully saturated soil will likely be the highest due to the lower effective stress of the soil below the foundation in this saturation condition. Based on the results from the second set of analyses, although uncertain, it is likely that inertial forces transmitted to the superstructure in the rocking isolated design are reduced. Both comparisons will shed light on the collective impact of SFSI, soil versus structure yielding, and the degree of water saturation on the seismic response of soil-foundation-structure systems.

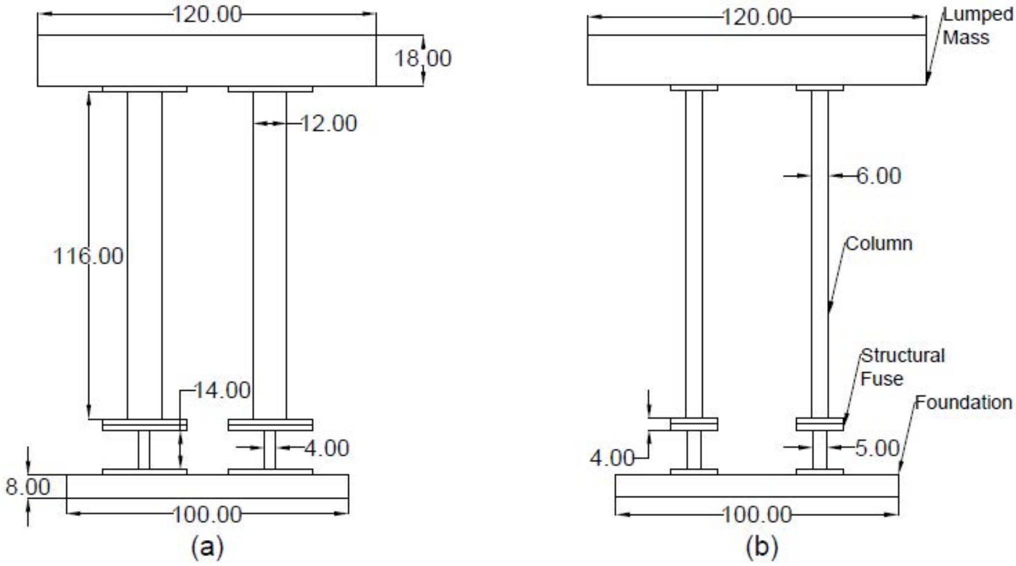

Figure 2: Schematic layout of the second physical model showing locations of structural fuses, model scale dimensions in mm. (a) Front view; (b) profile view.