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Seismic behavior of pile-supported systems in unsaturated sand

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ABSTRACT

The seismic behavior of pile-supported systems has been an active area of research over the past decades. However, focus has mostly been on evaluating the seismic response of structures embedded in either dry or fully saturated soil conditions. In this study, series of dynamic centrifuge tests were conducted to investigate the effects of soil's degree of saturation on the seismic behavior of pile-supported superstructures. The scaled physical model tests were carried out on two distinct pile-mass systems embedded in uniform sand layers. A steady state infiltration technique was used to control matric suction profiles in the sand layer prior to shaking. The obtained results from these experiments were illustrated in terms of peak accelerations, peak lateral displacements, and frequency content of the structural motion. The observed response showed higher acceleration amplification and lower lateral deformation for the pile-supported systems with foundations embedded in unsaturated sand comparing with those in dry sand. An inverse simple pseudo-static analysis was performed to back-calculate soil modulus values from the pile lateral deformations. The calculated values of soil modulus were higher for unsaturated sands showing consistency with the effect of matric suction on increasing the soil stiffness.

1. Introduction

Seismic behavior of pile-supported superstructures (e.g. bridges, elevated highways, offshore structures) is complex and controlled by different factors including inertial loads imposed by the superstructure, kinematic interaction caused by lateral movements of the soil layer, and the nonlinear stress-strain response of the supporting ground in strong shaking events. Further complexity is added to the problem in the cases of soil-pile gap formation or cyclic degradation of pile lateral stiffness due to pore pressure build-up in liquefying ground. Soil-structure interaction generally reduces the seismic demand by elongating the dominant period of the pile-supported superstructure and by increasing the system damping. However, it may cause strong bending moments and large permanent lateral deformations in the pile and surrounding soil, particularly in the cases of weak ground conditions or heavily loaded structures.

Several analytical and numerical models [1–7] have been proposed to simulate the seismic response of piles considering soil-pile interaction effects. The cornerstone of these methods has been the determination of the dynamic resistance of the soil layer to the pile motion. In these methods, the supporting soil is modeled using beam-on-Winkler springs concept and the soil elements are mostly presented by equivalent springs and dashpots accounting for the soil stiffness and damping, respectively. Soil-pile-structure interaction effects also have been investigated through well documented centrifuge and shaking table experiments [8–13] and field investigations [14,15]. These investigations played significant role in capturing realistic nonlinear soil-pile behavior and verifying numerical models. However, the focus of these studies on soil-pile-interaction has been on modeling pile-supported systems in dry or saturated soils, particularly in the worst-case conditions of liquefying and laterally spreading ground. In certain real field scenarios, as in arid or semi-arid regions, the ground condition is not at fully saturated state and the degree of saturation profiles with depth vary seasonally due to either climate weather conditions or changes in the ground water level. Unsaturated soils were shown to have different dynamic characteristics when compared with dry or saturated soils. Presence of both air and water in the void space results in inter-particle contact forces in the soil, increasing the effective stress and stiffness [16]. These changes in soils' state of stress affect the dynamic properties of soils including shear wave velocity, shear modulus, and damping ratio [17–30], as well as the seismic response of soil layers [31–34]. The different dynamic material characteristics and seismic response in unsaturated soil layers may affect the coupled seismic soil-pile-structure response; especially in the shallow soil layers. Thus,

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investigating the significance and extent of this effect would advance the state-of-the-knowledge in performance assessment of pile-supported structures in unsaturated soils.

The effect of degree of saturation on seismic soil-pile interaction has received very limited attention in the past. For example, Ravichandran et al. [35] conducted proof of concept centrifuge tests to evaluate the effect of degree of saturation on the static and dynamic response of pile foundations. Weaver and Grandi [36] successfully evaluated the applicability of the p-y curves for unsaturated soils (c-φ, p-y curves), proposed by Mokwa et al. [37], through 3-dimensional finite element analysis. The reported results of these studies, however, have been inadequate or inconclusive, requiring further comprehensive research in this area.

The objective of this paper is to present a physical modeling program using geotechnical centrifuge, aimed to investigate the effect of the degree of saturation of a fine sand on the seismic behavior of pile-supported structures. The steady state infiltration technique [32,38] was used in this study to develop a relatively uniform degree of saturation profile along the soil layer. The experimental program, and the observed seismic response (in terms of acceleration, lateral displacement, and frequency content) of two distinct pile-supported systems under various degrees of saturation are explained. Particularly, pile lateral displacement results were used to back-calculate unsaturated soil stiffness through an inverse pseudo-static analysis. It is expected that the results from this study provide insight into the effect of degree of saturation on the lateral response of pile-supported structures.

2. Experimental setup

2.1. Centrifuge facility

Centrifuge modeling was adopted to investigate possible effects of soils' degree of saturation on soil behavior and the performance of superstructures in soil-pile-structure systems. The 5-g ton centrifuge facility at the University of New Hampshire was used to perform scaled physical modeling tests in this study. The specimens were prepared in a laminar container with inside dimensions of 35.6 cm in length, 17.8 cm in width, and 25.4 cm in depth. The container is composed of 19 rectangular aluminum rings, each 12.7 mm thick, and separated by low friction cylindrical bearings, to reduce possible boundary effects during shaking [39]. The container was modified for experiments on unsaturated soils by replacing the base plate with an aluminum plate having a network of 4 drainage ports to allow free water drainage during the experiments. An inflight 1-D shaking table mounted on the centrifuge platform was used to impose model earthquakes or cyclic loads on the soil-pile-structure systems. The shaking table is driven by a servo hydraulic actuator, which is operated by a National Instruments control system and has an analog displacement limit of 10 mm. Four fluid lines including two lines for the hydraulic oil and two for the infiltrating water were supplied through the centrifuge slip ring.

2.2. Infiltration system

A 3D schematic of the infiltration system and the laminar container is illustrated in Fig. 1. To introduce partial saturation in the soil layer, an infiltration setup similar to that of Mirshekari and Ghayoomi [32] was used in this study. The reasons for choosing this technique were, first, its convenience in centrifuge modeling, and second, the possibility of desaturating the soil layer after pile installation. Water was used as the pore fluid in the system to facilitate the infiltration process. It is common to use a substitute fluid more viscous than water in centrifuge seismic modeling of saturated soils to overcome time-scaling conflict between dynamic and diffusion problems. However, in unsaturated soils, matric suction changes during dynamic loading as a result of formation and breakage of water menisci between soil particles, following a different mechanism from generation and dissipation of pore pressure in saturated soils. In the experiments carried out in this study, degrees of saturation were maintained lower than 60% to avoid such conflict. A 300 liter pressurized tank, placed outside the centrifuge, was used to supply the inflow water to the system. A set of eight BETE 1/8PJ20 spraying nozzles were mounted on two steel brackets above the container to spray water over the soil layer. The rate of the inflow water was defined by adjusting an ultra-precision needle valve before spinning while opening the inflow water was controlled by a solenoid valve during spinning. The brackets holding the spraying nozzles were placed along the shaking direction of the system, each within a safe lateral distance from the pile-supported systems to avoid any collision during shaking. The superstructures were also designed to oscillate in a safe height above the nozzle brackets to avoid their interference with the mist cone generated by the nozzles. Drainage was conducted using 4 miniature solenoid valves to guide the water flow to four outflow tanks mounted on the centrifuge platform at each side of the laminar container.

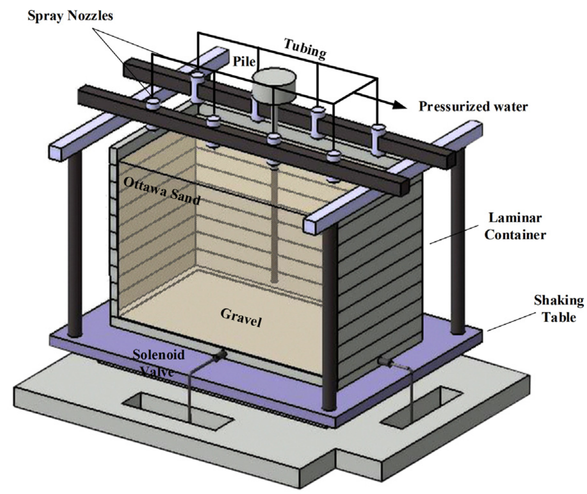

Fig. 1. 3D schematic of the infiltration setup mounted on centrifuge platform.

2.3. Description of physical models

Two pile-supported superstructure systems (System 1 and System 2) with distinct dynamic characteristics were modeled in this study. The structures were modeled as single degree of freedom systems, simulating the seismic response of, for example, bridge pillars. The fixed base natural period of the structural systems was chosen between 0.5 and 1.5 s to conform to the real field scenarios. In this study, tests were performed at 50*g* gravitational acceleration and the prototype properties were scaled accordingly. For the case of piles under lateral loading, an appropriate dimensionless parameter, which describes the soil-pile relative stiffness, is presented by Gl^4/EI [40]. In this equation, G is the soil shear modulus, l is the pile length, E is the elastic modulus of pile material and I is the area moment of inertia of pile section. To determine the scaled dimensions of the model, the abovementioned dimensionless ratio was maintained identical in the prototype and the model. The prototype and the equivalent model properties of the employed systems are provided in Table 1.

The supporting soil was modeled based on a prototype 11.4-m uniform layer of F-75 Ottawa sand. The geotechnical and hydraulic properties of this soil are summarized in Table 2. The selection of F-75 Ottawa sand, which is a fine and uniformly graded silica sand, was due to its relatively high permeability suitable for infiltration experiments in the centrifuge, as well as its sufficient fine particles that can retain water up to 10 kPa suction. Additionally, Ottawa sand is fine enough to satisfy the particle size requirement and eliminate the grain size scaling problem in centrifuge modeling. In this study, the ratio between the