Earthquake Induced Lateral deformation of a Pile-Supported System in Unsaturated Sand

PBD III VANCOUVER
Earthquake Geotechnical Engineering

Sahar Ghadirianniari & Ali Khosravi
Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
Morteza Mirshekari & Majid Ghayoomi
Department of Civil and Environmental Engineering, University of New Hampshire, Durham, NH, USA

ABSTRACT

Soil-pile-structure interaction and its effects on overall response of infrastructure have been an active area of research over the last several decades. However, focus has been mostly on developing methods of quantification for structures interacting with soils in dry or saturated conditions. In this study, a series of seismic centrifuge tests were conducted in an attempt to characterize the effects of degree of saturation on lateral response of soil-pile-structure systems. The scaled physical model tests were carried out on a single pile-mass system embedded in a 11-m layer of Ottawa sand with D_r of about 45%. A steady state infiltration technique was used inside a laminar box mounted atop an inflight shake table to provide uniform suction profiles through the sand layer during shaking. In this paper, the model development and construction procedure are explained followed by comparison of lateral deformation at different levels. Overall, unsaturated soil layers resulted in lower lateral deformation due to the presence of suction and higher shear modulus in soil. This difference was more significant at the superstructure level where more deformations were introduced.

1 INTRODUCTION

Seismic performance of pile-supported structures (e.g. bridges, elevated highways, tall buildings on weak ground) is a complex phenomenon, which requires consideration of the coupled behavior of soil-pile-superstructure system. As seismic waves propagate through the soil layers, the pile foundation tends to modify the transmitted motion due to the soil-pile stiffness contrast and the incoherent deformations of the pile and the surrounding soil; i.e. kinematic interaction. Simultaneously, the vibration of the superstructure causes additional deformations and stresses in the pile and the surrounding soil, resulting in inertial interaction. The induced interactions may alter the structural response of the pile-supported systems including superstructure lateral deformation, pile bending moments, and frequency content of the motion.

In the past few decades, well-documented physical modeling and field monitoring data have demonstrated the significance of soil-pile interaction effects on seismic performance of pile-supported structures (Makris et al. 1997, Boulanger et al.1999, Wilson et al. 2000, Abdoun et al. 2003, Tokimatsu et al. 2005, Dobry et al. 2005). The focus of these studies, however, has been on evaluating the seismic performance of pile foundations embedded in dry or liquefying grounds. In many real field scenarios, as in arid or semi-arid regions, soil becomes partially saturated, with degree of saturation profiles varying seasonally due to changes in the groundwater level. In these scenarios, understanding the effect of partial saturation on soil-structure interaction may result in a more precise assessment of the performance of pile-supported structures in different times.

The impact of soil's degree of water saturation on soil-pile interaction and the overall seismic response of a pile-supported structure can be significant. Presence of both air and water inside a void of an unsaturated soil may result in generation of some inter-particle contact forces in soil, generating suction and increasing effective stress (Lu and Likos 2006). These changes in soil's state of stress may affect soil's dynamic characteristics including shear wave velocity, shear modulus, and damping ratio (Wu et al. 1984, Qian et al. 1991, Yang et al. 2000, Mancuso et al. 2002, khosravi et al. 2010, Khosravi and McCartney 2011, Khosravi and McCartney 2012, Ghayoomi and McCartney 2011, Ghayoomi et al., 2011, Hoyos et al. 2015, Khosravi et al. 2016a, Khosravi et al. 2016b, Khosravi et al. 2016c), as well as its seismic response (D'Onza et al. 2008, Ghayoomi and Mirshekari 2014, Mirshekari and Ghayoomi 2017).

Previous studies have addressed the seismic response of partially saturated soils through analytical and physical modelling. However, the effect of partial saturation on seismic soil-pile interaction has not been fully investigated through a systematic experimental program and only few studies have considered or discussed the mechanisms involved in soil-pile interaction with unsaturated soils (Weaver and Grandi 2009, Ravichandran et al. 2012, Ravichandran et al. 2013). For example, Ravichandran et al. (2013) conducted a series of centrifuge tests to evaluate the effect of degree of saturation on the static and dynamic response of pile foundations. The obtained results, however, could not represent any noticeable effect as a narrow range of soil's saturation degree was selected for the tests.

The objective of this research is to present a physical modeling program, aimed to investigate the effect of degree of saturation on seismic soil-pile-structure interaction. The experimental program and seismically induced lateral deformation of a pile-supported structure under various degrees of saturation is explained in this paper. A series of seismic centrifuge tests were conducted where a single pile with a concentrated mass on its top as the superstructure was embedded in a uniform layer of sand. The steady-state infiltration technique was used to develop a relatively uniform degree of saturation profile along the specimen where different degrees of saturation were obtained by varying the discharge velocity. The results from these tests were compared with the observed response of the system in dry soil to provide insight on the effect of degree of saturation on the seismic behavior of the system.

2 EXPERIMENTAL SETUP

2.1 Centrifuge facility

A mid-size 5-g ton geotechnical centrifuge, available at the University of New Hampshire was used to perform the physical modelling in this study. The centrifuge has a 1-meter radius and is equipped with an in-flight 1-D shaking table driven by a servo hydraulic actuator. A laminar container with inside dimensions of 35.6 cm long, 17.8 cm wide, and 25.4 cm deep was used to effectively reduce boundary effects. The laminar container was modified for experiments on unsaturated soils by replacing the base laminate with an outflow aluminum plate providing a network of drainage holes to allow free water drainage during the experiments. All the tests were conducted at the centrifuge acceleration of 50g measured at the middle of the soil specimen. All dimensions referenced in this report are in prototype units unless noted otherwise.

2.2 Infiltration Setup

The infiltration setup used in this study is similar to that of Mirshekari and Ghayoomi (2017). A pressurized tank placed outside the centrifuge supplied the inflow water. A set of eight nozzles were mounted on two steel brackets above the container to spray water over the soil layer.

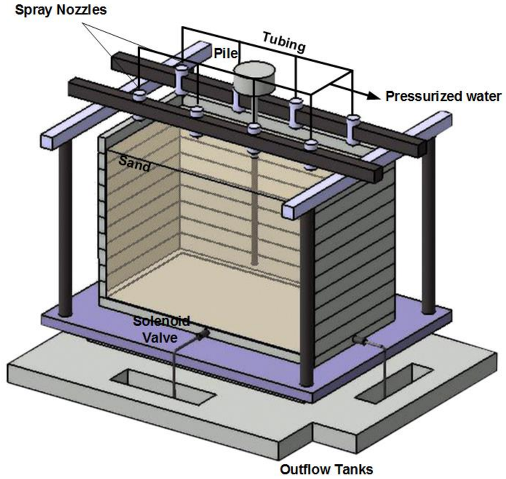

Figure 1. Schematic of the infiltration set up.

A solenoid valve was employed to control the inflow of water during the centrifugation, while the rate of inflow was adjusted by using an ultra-precision needle valve before spinning. The nozzles and the holding brackets were located at two sides of the pile-supported system within a safe distance from the pile system to avoid any collision during the shaking event. The superstructure was designed to stay higher than the brackets to avoid interfering with the cone of mist generated by the nozzles. Four miniature solenoid valves were used to control the outflow water through the drainage ports to four outflow tanks mounted on the centrifuge platform at each side of the container. A 3D schematic of the infiltration setup is illustrated in Figure (1).

2.3 Model Descriptions

An 11.43 m layer of F-75 Ottawa sand was modeled in this study. This sand has enough fine particles to retain water up to 10 kPa of matric suction, and a relatively high permeability to allow for steady state infiltration. The geotechnical properties of the material are summarized in Table (1). Soil Water Retention Curve (SWRC) of the sand measured by Mirshekari and Ghayoomi (2015) along with the fitted van Genuchten equation (van Genuchten 1980) are shown in Figure (2).

Table 1. Soil properties.

Parameter	Value
C_c, C_u	1.71, 1.01
D_{50}	0.182
e_{max}, e_{min}	0.8, 0.49
ρ_{max}, ρ_{min}	1781,1469
Saturated hydraulic conductivity, K_s (cm/s)	$6x10^{-4}$

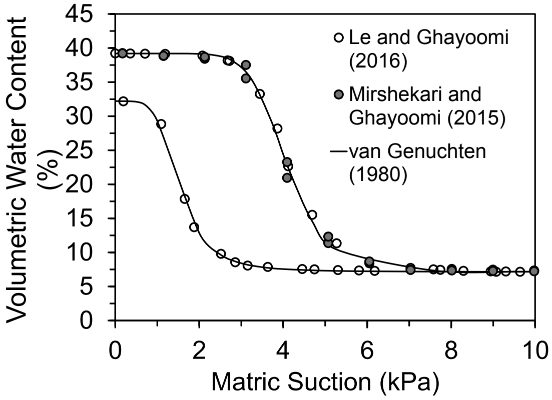

Figure 2. SWRC of Ottawa Sand.

The pile-supported superstructure model used in the tests was equivalent to a prototype Flexible steel pipe (based on the criteria by Tomlinson and Woodward 2014) with the properties given in Table 2. The system was instrumented with a LVDT, accelerometers, and dielectric sensors to measure displacement, acceleration, and volumetric water content, respectively. The instrumentation layout is shown in Figure (3). A series of six accelerometers were located on the superstructure and at different depths to record acceleration time histories throughout the soil specimen, pile, and the structure. Four dielectric sensors were used at different depths to measure the degree of saturation profile through the sand layer and also to assure its uniformity prior to the shaking. The LVDT was mounted on top of the container to measure the surface settlement of the sand layer during different processes of water saturation, desaturation, and shaking.

Table 2. Prototype characteristics of the pile-supported system.

Characteristic	Value
Pile Length (m)	8.5
Pile Outside diameter (m)	0.5
Wall thickness (m)	0.05
Superstructure Height (m)	6.4
Superstructure Weight (kN)	310
Fixed base period of the structure (s)	0.67

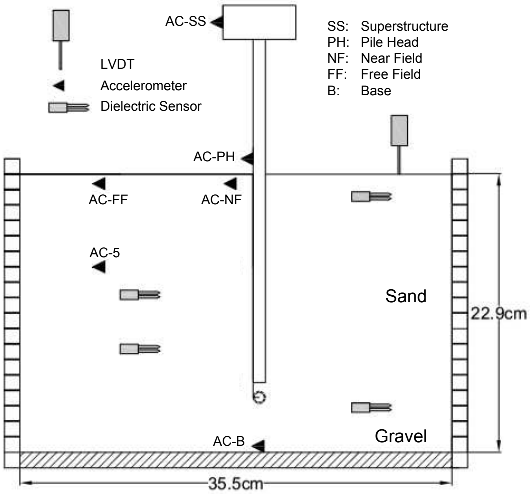

Figure 3. Schematic of layout and instrumentation (Dimensions are in model scale).

3 TESTING PROCEDURE

A thin gravel layer was placed at the base of the laminar container to provide a saturated boundary condition at the bottom. The gravel layer was separated from the overlying sand by using a geotextile fabric. Dry pluviation was used to prepare a uniform sand layer with a relative density, D_r, of 45%. Instrumentations were placed at different depths during the pluviation. After preparing the sand layer, the pile was installed at 1g (prior to shaking), using a drop hammer with a constant drop height of 2.54 cm. The driving method was used to provide adequate lateral resistance for the pile as it was installed in loose sand. Modeling the ground condition with a loose uniform sand layer may not conform to realistic field scenarios for driven piles, as these piles are often driven in dense ground or fixed at the bedrock. Nonetheless, assuming a uniform loose sand layer allowed an effective desaturation process of the soil layer in this study, and simplified the problem where the direct effect of the degree of saturation on the lateral response can be evaluated.

The specimen was, first, fully saturated prior to spinning by passing de-aired water through the drainage ports of the laminar container. Then, the specimen was spun up to the target acceleration level when the infiltration started by adjusting the inflow and outflow solenoid valves. Steady state condition with uniform degree of saturation profile within the soil was reached after a short period of infiltration. The target degree of saturation in each test was obtained by adjusting the needle valve for the corresponding inflow rates.

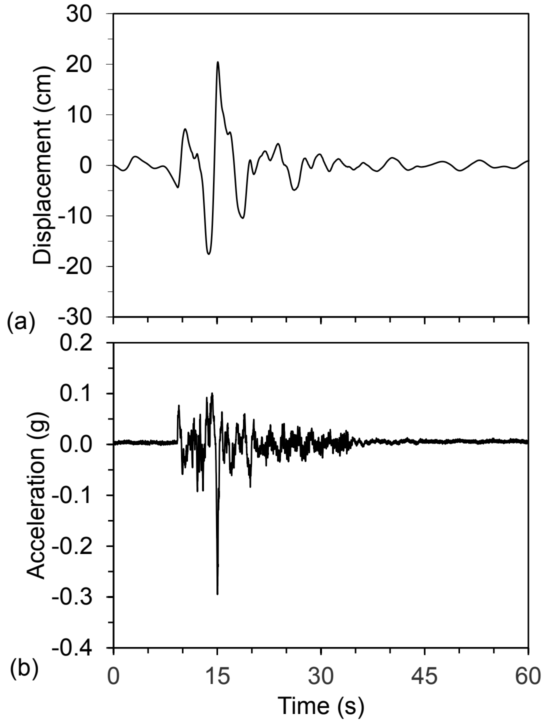

Figure 4. Recorded Earthquake Motion at the base of the container: (a) Displacement time history, (b) Acceleration time history.

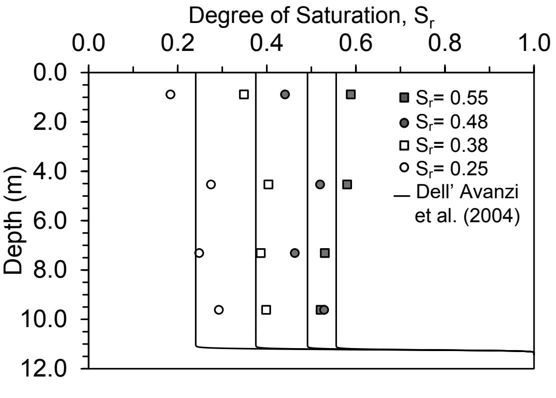

Figure 5. Profiles of soil saturation degrees along with the (Dell' Avanzi et al. 2004)

The obtained experimental saturation profiles along with the fitted steady state infiltration equation proposed by Dell' Avanzi et al. (2004) are presented in Figure (5). The model was, then, subjected to the shaking event and the corresponding response was captured through the LVDT and accelerometers. Northridge earthquake motion, 1994, captured at WPI station was selected as the base input motion in this study due to its broad frequency range. In order to meet the hydraulic actuator limits, the peak ground acceleration was scaled down from 0.42g to 0.3g. The acceleration and displacement time histories of the scaled shaking event used in this study are shown in Figure (4).

4 RESULTS

Seismic results associated with five centrifuge tests are presented; one with the pile embedded in dry soil (test D1), and four with the pile embedded in soil with different degrees of saturation, ranging between 25% and 55% (tests U25, U38, U48, U55, with U indicating the unsaturated condition and the values corresponding to the soil's degree of saturation in percent). Measured displacement time histories for several points in the sand layer and on the pile-structure system for tests D1 and U48 are shown in Figures 6(a) and 6(b), respectively.

These responses were obtained by double integration and baseline correction of the recorded data from the accelerometers presented in Figure (3). Based on the results presented in these figures, displacement was amplified from the free field to the superstructure, especially at higher frequencies. The results showed lower displacement amplifications of both the soil and the superstructure for the unsaturated test (U48) as compared to dry test. Relative peak lateral displacement profiles of free-field soil and the pile system with respect to the soil base for U48 and D1 tests are shown in Figure (7). Comparison of the achieved results shows that the relative peak lateral deformation of the free field motion in test U48 is slightly lower than that of D1 throughout the depth. The observed response could be due to the presence of the inter-particle contact forces in unsaturated sand, which had resulted in higher stiffness and lower induced shear strains and lateral deformations. The shear modulus of the soil can well replicate this trend as it was observed to be higher for unsaturated sand, especially for the range of soil suction examined in this study (Ghayoomi et al. 2013). However, the range of variation in the stiffness of unsaturated sand and its overall effect on the deformation behavior in this study is limited due to small suction stresses introduced in such fine-grained, clean sand.

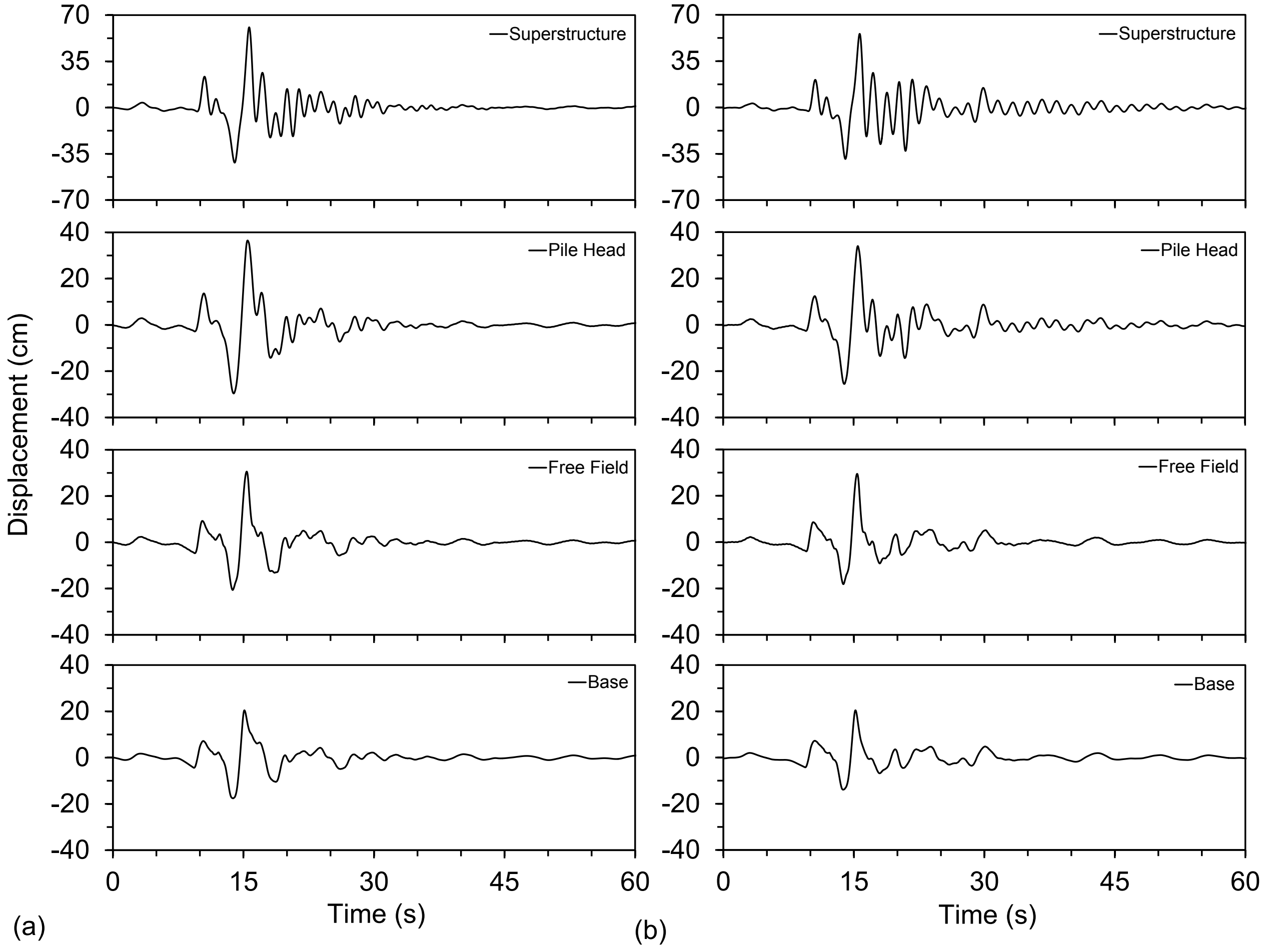

Figure 6. Displacement time histories for system in: (a) Dry soil (D1); (b) Soil with saturation degree of 0.48. (U48)

Further, the relative peak lateral deformation profiles of the pile-supported system in Figure (7) show that the peak values are also lower in U48 as compared to D1. This difference, though, is more noticeable due to the larger interactions between the superstructure and the surrounding soil. When a pile element undergoes a complex horizontal displacement, it meets a horizontal soil reaction, which is a function of soil shear modulus (G), Poisson's ratio (v), mass density (ρ), material damping (D), pile slenderness (L/r), and excitation frequency (Novak 1974). The observed results showed that higher shear modulus values in unsaturated sand as compared to dry sand resulted in a stronger soil reaction and lower maximum lateral displacement in the pile and the superstructure.

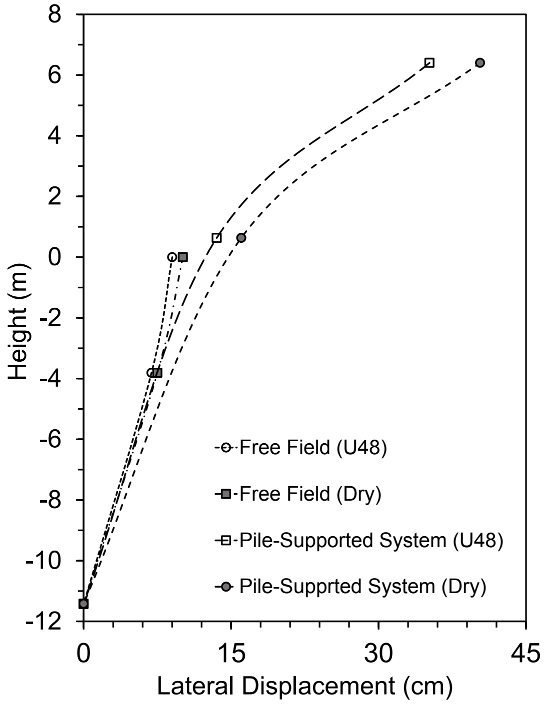

Figure 7. Peak relative lateral displacement profile of the pile-supported system and free field for tests D1 and U48.

In order to better understand the overall impact of degree of saturation on the lateral soil and pile deformation, the relative peak lateral deformation of the superstructure, pile head, free field and near field soils under various degrees of saturation are compared in Figure (8). The results of these experiments indicated lower values of lateral displacement for the systems with $S_r > 0$. However, for the range of saturation degrees considered in this study, the effect of saturation on the seismic response of the soil-pile-superstructure system was not significant. For example, for the superstructure, a 10 to 12 % decrease in superstructure's lateral displacement was observed with 50% increase in soil's degree of saturation. Very similar trends were observed when plotting the peak lateral deformation in terms of soil suction (Fig. 9). At suction levels greater than zero (ψ>0), the effective stress was expected to be higher and accordingly, lower pile and superstructure lateral displacements were measured.

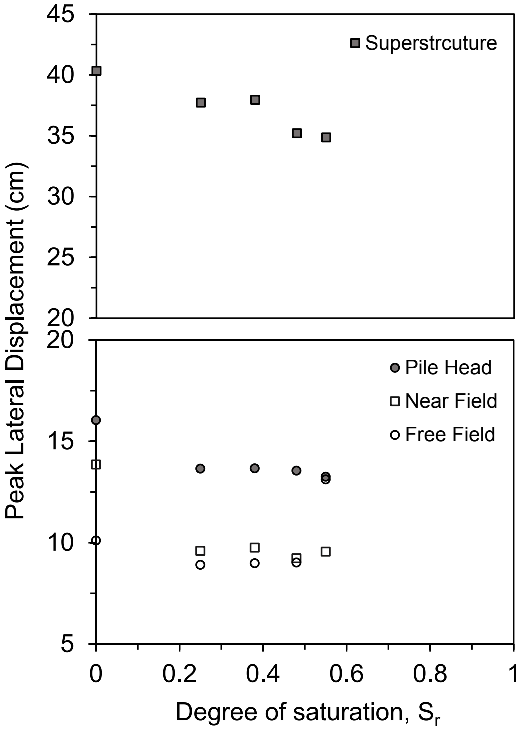

Figure 8. Peak relative lateral displacement values for different degrees of saturation.

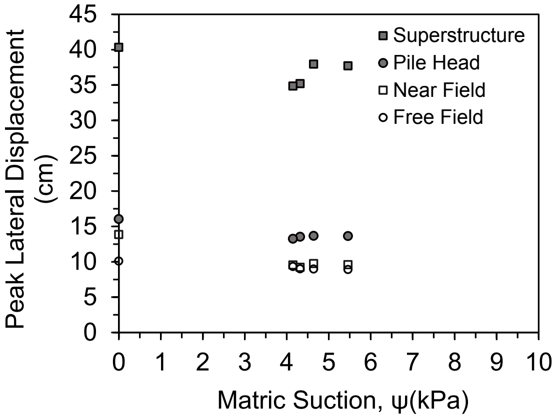

Figure 9. Peak relative lateral displacement values for different suction levels.

5 CONCLUSIONS

A centrifuge physical model was developed and tested to evaluate the earthquake induced lateral deformation of a pile-supported superstructure in sand layers with various degrees of saturation. Steady state infiltration technique was successfully used to control the degree of saturation in the sand layer where the model pile was embedded. The observed deformations of both the pile-supported structure and the soil were lower for unsaturated soil states. Especially a 10-12% decrease in the lateral deformation of the superstructure was observed with 50%

increase in soil degree of saturation. The observed behavior was probably due to higher effective stress and stiffness in the soil layer with degrees of saturation greater than zero, which caused lower shear strains and deformations in the soil and the pile-supported system. However, a nonlinear, limited change in peak lateral deformation was observed for soils with different degrees of saturation due to the narrow range of suction stress level in this unsaturated sand, especially for the range of degree of saturation examined in this study.

REFERENCES

Abdoun, T., Dobry, R., O'Rourke, T. D., & Goh, S. (2003). Pile response to lateral spreads: centrifuge modeling. *Journal of Geotechnical and Geoenvironmental Engineering, 129*(10), 869-878.

AVANZI, E. D., Zornberg, J. G., & Cabral, A. R. (2004). Suction profiles and scale factors for unsaturated flow under increased gravitational field. *Soils Found, Vol. 44(3), pp. 79–90.*

Boulanger, R. W., Curras, C. J., Kutter, B. L., Wilson, D. W., & Abghari, A. (1999). Seismic soil-pile-structure interaction experiments and analyses. *Journal of Geotechnical and Geoenvironmental Engineering, 125*(9), 750-759.

d'Onza, F., d'Onofrio, A., & Mancuso, C. (2008). Effects of Unsturated Soil State on the Local Seismic Response of Soil Deposits. *Proc. 1st European Conf. on Unsaturated Soils, Durham, UK, 2008;* 531- 536.

Dobry, R., Abdoun, T., O’Rourke, T. D., & Goh, S. (2005). Closure to “Single Piles in Lateral Spreads: Field Bending Moment Evaluation”. *Journal of Geotechnical and Geoenvironmental Engineering, 131*(4), 532-534.

Ghayoomi, M., McCartney, J., & Ko, H.-Y. (2011). Centrifuge test to assess the seismic compression of partially saturated sand layers. *ASTM Geotechnical Testing Journal, 34(4).321-331*.

Ghayoomi, M. & McCartney, J. S. (2011). Measurement of small-strain shear moduli of partially saturated sand during infiltration in a geotechnical centrifuge. *ASTM Geotechnical Testing Journal, 2011, 34(5), 10 pg.*

Ghayoomi, M., McCartney, J. S., & Ko, H.-Y. (2012). Empirical methodology to estimate seismically induced settlement of partially saturated sand. *Journal of Geotechnical and Geoenvironmental Engineering, 139*(3), 367-376.

Ghayoomi, M., & Mirshekari, M. (2014). Equivalent linear site response analysis of partially saturated sand layers*. Paper presented at the UNSAT2014 conference, Sydney, Australia.*

Hoyos, L. R., Suescún-Florez, E. A., & Puppala, A. J. (2015). Stiffness of intermediate unsaturated soil from simultaneous suction-controlled resonant column and bender element testing. *Engineering Geology, 188*, 10-28.

Khosravi, A., Ghadirian, S., & McCartney, J. (2016). Effect of Subsequent Drying and Wetting on the Small Strain Shear Modulus of Unsaturated Soils. *World Academy of Science, Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 10*(2), 202-207.

Khosravi, A., Ghayoomi, M., McCartney, J., & Ko, H.-Y. (2010). Impact of effective stress on the dynamic shear modulus of unsaturated sand. *Advances in Analysis, Modeling & Design. ASCE, 199*, 410-419.

Khosravi, A., Gheibi, A., Rahimi, M., McCartney, J., & Haeri, S. (2016). Impact of void ratio and state parameters on the small strain shear modulus of unsaturated soils. *Japanese Geotechnical Society Special Publication, 2*(4), 241-246.

Khosravi, A., & McCartney, J. S. (2011). Resonant column test for unsaturated soils with suction–saturation control. *ASTM Geotech. Test. J., 34(6), 1-10*

Khosravi, A., & McCartney, J. S. (2012). Impact of hydraulic hysteresis on the small-strain shear modulus of low plasticity soils. *Journal of Geotechnical and Geoenvironmental Engineering, 138*(11), 1326-1333.

Khosravi, A., Salam, S., McCartney, J. S., & Dadashi, A. (2016). Suction-induced hardening effects on the shear modulus of unsaturated silt. *International Journal of Geomechanics, 16*(6), D4016007.

Lu, N., & Likos, W. J. (2006). Suction stress characteristic curve for unsaturated soil. *Journal of Geotechnical and Geoenvironmental Engineering, 132*(2), 131-142.

Makris, N., Tazoh, T., Yun, X., & Fill, A. (1997). Prediction of the measured response of a scaled soil-pile-superstructure system. *Soil Dynamics and Earthquake Engineering, 16*(2), 113-124.

Mancuso, C., Vassallo, R., & d'Onofrio, A. (2002). Small strain behavior of a silty sand in controlled-suction resonant column torsional shear tests. *Canadian geotechnical journal, 39*(1), 22-31.

Mirshekari, M. and Ghayoomi, M. (2017). Centrifuge Tests to Assess Seismic Site Response of Partially Saturated Sand Layers. Submitted to Journal of Soil Dynamics and Earthquake Engineering.

Mirshekari, M., & Ghayoomi, M. (2015). Simplified equivalent linear and nonlinear site response analysis of partially saturated soil layers. *IFCEE 2015* (pp. 2131-2140).

Novak, M. (1974). Dynamic stiffness and damping of piles. *Canadian geotechnical journal, 11*(4), 574-598.

Qian, X., Gray, D. H., & Woods, R. D. (1991). Resonant column tests on partially saturated sands.

Ravichandran, N., Bhuiyan, A., & Huggins, E. (2012). Dynamic Analysis of Unsaturated Soil-Pile System Using Simplified Finite Element Formulation *GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering* (pp. 2462-2471).

Ravichandran, N., Krishnapillai, S. H., & Machmer, B. (2013). A novel procedure for physical modeling of unsaturated soil-pile system using geotechnical centrifuge. *J. Earth Sci. Geotech. Eng, 3*(1), 119-134.

Tokimatsu, K., Suzuki, H., & Sato, M. (2005). Effects of inertial and kinematic interaction on seismic behavior of pile with embedded foundation. *Soil Dynamics and Earthquake Engineering, 25*(7), 753-762.

Tomlinson, M., & Woodward, J. (2014). *Pile design and construction practice*: CRC Press.

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil science society of America journal, 44*(5), 892-898.

Weaver, T. J., & Grandi, O. (2009). Lateral Load Analysis of Deep Foundations in Unsaturated Soils *Contemporary Topics in In Situ Testing, Analysis, and Reliability of Foundations* (pp. 552-559).

Wilson, D. W., Boulanger, R. W., & Kutter, B. L. (2000). Observed seismic lateral resistance of liquefying sand. *Journal of Geotechnical and Geoenvironmental Engineering, 126*(10), 898-906.

Wu, S., Gray, D. H., & Richart Jr, F. (1984). Capillary effects on dynamic modulus of sands and silts. *Journal of Geotechnical Engineering, 110*(9), 1188-1203.

Yang, J., & Sato, T. (2000). Effects of pore-water saturation on seismic reflection and transmission from a boundary of porous soils. *Bulletin of the Seismological Society of America, 90*(5), 1313-1317.