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A Novel Procedure for Physical Modeling of Unsaturated Soil-Pile System Using Geotechnical Centrifuge

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Abstract

The mechanical and flow behaviors of unsaturated soil are affected by the degree of soil saturation, the load carrying capacity of pile foundations supported on unsaturated soils are affected as well. This paper describes a geotechnical centrifuge testing procedure developed for evaluating the effect of degree of saturation on the static and dynamic response of pile foundations. Specifically, the specimen preparation, testing procedure, and sample test results are presented. A uniform degree of saturation profile with depth was obtained by spraying water from the top of the model. The water was stored in a pre-pressurized inflow tank attached to the centrifuge platform. The flow rate was controlled using servo valves, and the model dimensions were scaled using centrifuge scaling laws. The experiments were conducted in Ottawa sand at 50 g centrifugal accelerations. Results from 24% and 28% degree of saturations are presented with important suggestions based upon our experience.

Keywords: Unsaturated soil-structure interaction, unsaturated soil-pile interaction, unsaturated soil, centrifuge modeling, physical modeling, and centrifuge testing method.

1 Introduction

Pile foundations, the essential components of many civil engineering structures, are often located in zones of unsaturated soils. The soil-pile interaction is a complex phenomenon to investigate, the complexity of which is further magnified when the pile foundation is

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supported by unsaturated soils and/or subjected to earthquake loads. The complexity from the supporting soil arises due to its multiphase nature and complex interactions. The unsaturated soil is a three phase medium that consists of three bulk phases and three interfaces between the bulk phases. Among the three interfaces, the air-water interface assumes a critical function in maintaining the pressure balance between the air and water phases. The mechanical behavior of unsaturated soil is governed not only by the behavior of the bulk phases and the interfaces but also by the interaction among various bulk phases and interfaces and their interaction with the pile foundation.

The evaluation of both lateral and axial load carrying capacity of the pile foundation is equally important in the design of such foundations that are susceptible to earthquake loads. The lateral load carrying capacity of pile foundations is significantly influenced by the stiffness of the supporting soils. In addition to many other factors, the stiffness of unsaturated soil is influenced by matric suction (pore air pressure minus pore liquid pressure) that is directly related to the degree of saturation of the soil through soil water characteristic curve. A more thorough elucidation of the effect of degree of saturation on the unsaturated soil-pile interaction is expected to be of use to practicing engineers to avoid over-conservative designs. It can also provide insights into the effect of degree of saturation on the shear wave propagation.

In their study of the influence of unsaturated condition on the axial capacity of pile foundation, Georgiadis et al. (2003) using the numerical method, determined that the axial capacity increases with suction, and also predicted an excessive settlement due to collapse of the soil under the pile tip. In that this excessive settlement could not be derived via finite element analysis using the saturated soil code (Georgiadis et al., 2003), it can be concluded that for a pile foundation, the critical condition occurs when soil are in unsaturated conditions where the fully saturated condition is not critical.

Centrifuge modeling of the unsaturated soil-pile systems is such viable option for an intuitive apprehension of the effect of degree of saturation on the pile response under controlled environment. Practical difficulties in maintaining a constant degree of saturation profile (suction profile) with depth throughout the duration of scrutiny has been the challenge when performing centrifuge tests and obtaining quality data to understand the effect of degree of saturation on the pile response. Here the authors created a procedure for creating and maintaining a constant suction profile throughout the analysis. Ancillary experimental results of the samples are also explained.

1.1 Centrifuge Modeling of Geotechnical Systems

Although the full scale experiments may provide more realistic data, compared to model scale experiments, conducting full scale experiments in a controlled environment is most demanding. In such cases physical modeling such as geotechnical centrifuge modeling are commonly used. With the recent advances in instruments and data acquisition systems and well defined centrifuge scaling laws, the factors that influence the behavior of complex soil-pile systems can be studied. In their study of the influence of soil type and soil density, Wilson (1998) determined that the behavior of soil-pile systems significantly varies with soil type and soil density. Similarly, their centrifuge study, Abdoun et al. (1997) deduced that the response of piles significantly depended upon the method by which the piles were installed. Loading type and loading rate were also found to be salient criteria (Tokida et al., 1992) affecting the pile response. In a complementary analysis, Liu and Dobry (1995) elucidated the importance of excess pore pressure ratio in affecting the overall response of soil-pile system. In addition, subsequent experimentation by a diverse group of scholars have substantially annotated the geotechnical and structural properties affecting the response of pile foundations supported by either saturated or dry soils (Finn and Gohl, 1987; Chang and Kutter, 1989; Café, 1991; Leung and Ko, 1993; Rashidi, 1994; Honda et al., 1994; Horikoshi et al., 1997; Michael et al., 1998; Bruno and Randolph, 1999; Ross et al., 1999; and Scott et al., 2007). These findings have been incorporated in the design and construction of pile foundations in seismically active areas. There has yet to be however, a comprehensive study to determine effect of degree of saturation of the supporting soil on the overall pile behavior for incorporation of these unsaturated soil characteristics into actual best practices. It is worthwhile mentioning here that the unsarturated soil mechanics has been incorporated into the design of shallow foundation (Fathi et al., 2010)

An incidental number of studies associated determining the properties unsaturated soils using geotechnical centrifuge have been conducted, however. In their 1997 study, Deshpande investigated the static and dynamic behavior of unsaturated silt embankment in geotechnical centrifuge. Here, soil was prepared with target degree of saturation and models were built with the moist soil. The measurements showed that measured degree of saturation immediately before spinning the centrifuge was not uniform and also significantly different from the initial degree of saturation at which the sample was prepared.

Soga et al. (2003) conducted a centrifuge modeling to study the movement and entrapment of water and of light nonaqueous phase liquids (LNAPLs) in unsaturated layered soil deposits. A similar study of the migration process of light nonaqueous phase liquids in unsaturated soils and soil vapor extraction was also conducted by Lo et al. (2005) using centrifuge modeling. Similarly, McCartney and Zornberg (2010) employed the centrifuge technique to study the hydraulic characteristics of unsaturated compacted clay and its soil-water retention characteristics and hydraulic conductivity characteristics.

1.2 Centrifuge Scaling Laws and Other Steps in Centrifuge Modeling of Dynamics of Soil-Pile Systems

Perhaps the most substantive procedure in centrifuge modeling entails prototypical scaling of the geometric and material parameters to corresponding model values the laws of the scaling centrifuge. These scaling laws are thusly informed via consideration of the identical stresses in prototype and model inflight so that the prototype responses can be calculated using the measured model responses and appropriate scaling factors. The linear dimensions are scaled by the factor 1/N in which N is the centrifugal acceleration, and the scaling laws for other basic parameters are summarized in Table 1.

Table 1: Commonly used scaling factors for centrifuge modeling.

Parameter	Scaling Factor (Prototype/Model)
Linear dimensions	N/1
Microscopic length	1
Time (dynamic)	N/1
Time (consolidation)	$N^2/1$
Acceleration, Gravity	1/N
Force	$N^2/1$
Fluid interfacial tension	1
Stress, Pressure, Strain	1/1
Flexural rigidity	$N^4/1$
Pore fluid velocity	1/N
Hydraulic conductivity	1/N
Porosity, density, viscosity	1

The procedure for soil-pile interaction modeling can be divided into three dominant phases. The first stage is the model construction that includes soil placement, pile installing, instrumentation and a special configuration for controlling the degree of saturation in the soil. The Dry Pluviation technique is commonly used to place dry soil in the model container at a desired relative density. The pluviation height (the height between the bottom of the funnel and the surface of the soil) has a direct correlation to the relative density of the soil (Whitman and Lambe 1988) with the relative density increasing with puluviation height. In the modeling of driven pile, piles are driven into the soil layer subsequent to the development of the soil profile. On the other hand, the pile is placed and secured prior to pulluviation for modeling drilled shafts. The disparate method employed to install the pile may also vary with the type of soil being used in the test. In saturated clayey soils, a hole can be pre-drilled after consolidating the layer and then the pile is pushed through the hole.

The other most important and difficult aspect concerning the centrifuge modeling of unsaturated soil is the configuration and procedure for obtaining uniform profile with a target degree of saturation. One such configuration used by the author in this study is described in the in detail below. Once the model is constructed, well-developed slandered centrifuge procedures to run tests and record measured data are subsequently undertaken.

2 Procedure for Achieving Uniform Soil Profile with a Target Degree of Saturation for Centrifuge Modeling of Unsaturated Soil-Pile System

A schematic of important components of the configuration is illustrated in Figure 1. Methods of infiltration have been developed to achieve a controlled suction profile in unsaturated soils, most specifically the Drainage-Recharge Method (Yegian et al. 2007) and Steady State Infiltration Method (Zornberg and McCartney 2010). Through these methods, a profile with different degrees of saturation can be achieved by changing the infiltration rate. The basic idea is to maintain a steady downward flow of water from the surface to the bottom of the soil, the application of which needs a mere two setups. They are (a) a remotely controllable steady inflow or precipitation setup, and (2) a remotely controllable outflow or drainage setup.

A steady precipitation is achieved by spraying water at the top of the sample. The major challenges entailing the use of the procedure involve identifying locations for nozzles, the height of the nozzles above the surface and the inflow water pressure for obtaining uniform precipitation without disturbing the surface soil. Instruments and other setups such as accelerometers, LVDTs, pile cap and lateral pile loading setups at the surface of the soil compounded the difficulty of this scheme. The final locations and the types of nozzles for the proposed static and dynamic soil-pile system were finalized after a series of trials. Dividing the central water supply tube to supply water to each nozzle must be done carefully to ensure an adequate supply of water to each nozzle with, thusly mandating a symmetrical split. The authors also emphasize the importance of closely monitoring the pressure of the water stored in the pre-pressurized inflow tank (tank #1), the air pressure of which affects the both the flow rate and water spray.

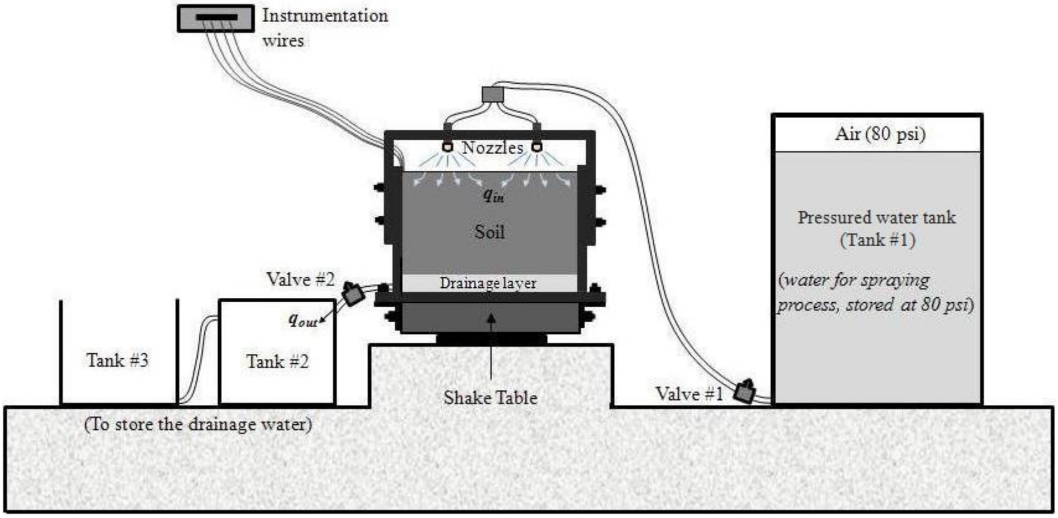


Figure 1: Schematic view of the flow distribution/collection system

To get the uniformity in the drainage/outflow, the scheme is designed for the proper placement of a drainage layer at the bottom of the model (i.e. below the soil layer that connects drainage tubes to all four sides of the model). The drainage tubes should be positioned as lower as possible within the depth of drainage layer. All the drainage tubes should be joined and connected to the valve #2 and then with the outflow tank (tank #2). The valves #1 and #2 can be controlled remotely to change the flow rate inflight.

3 Sample Application of the Procedure and Other Considerations

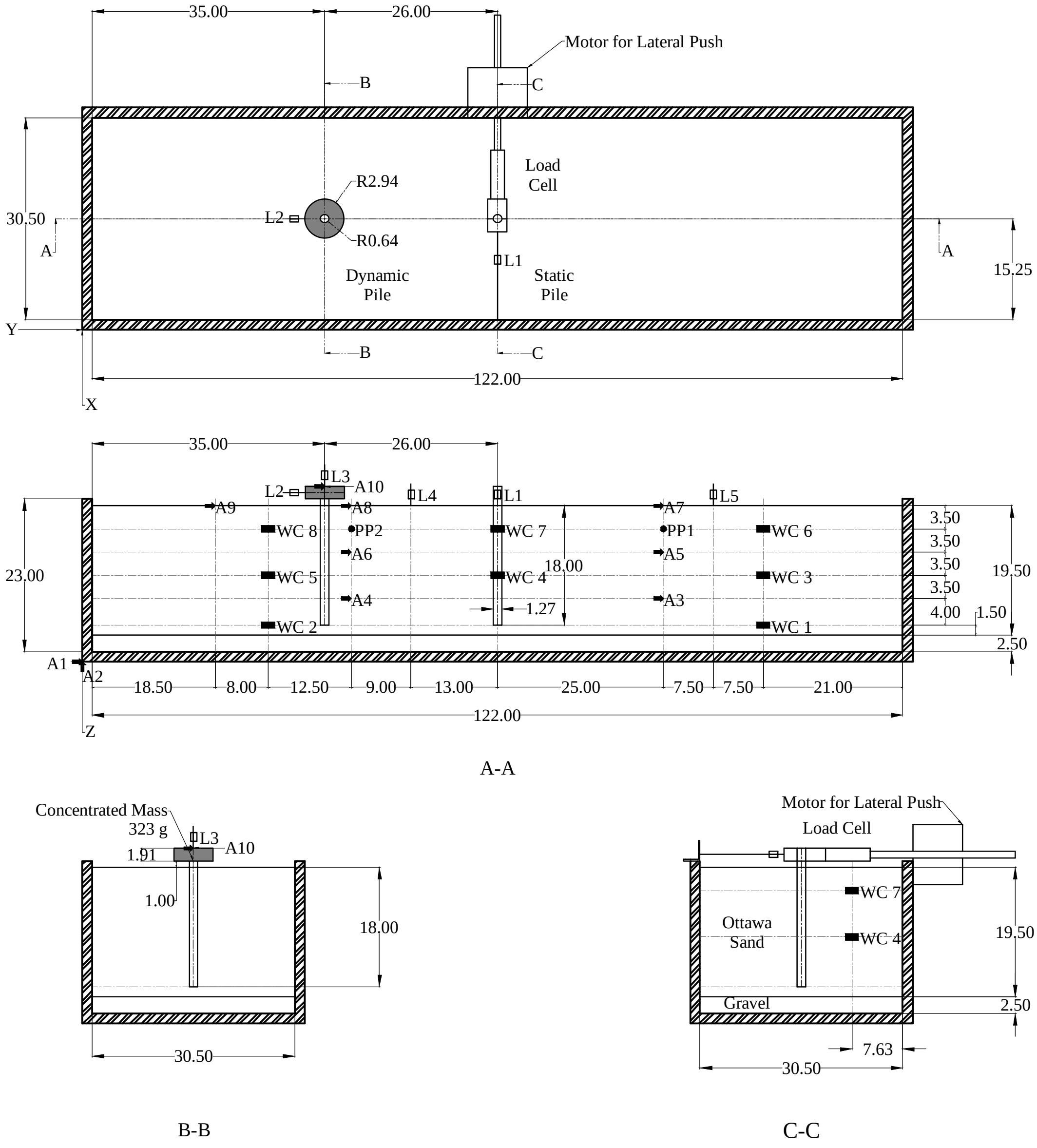
3.1 Problem Description

The behavior of 24 inch outside diameter steel pipe pile (an SCDOT standard pile) subjected to static-cyclic lateral load and dynamic load was modeled using the centrifuge facility available at the University of Colorado at Boulder. The major objective of this study was to understand the effect of degree of saturation on soil-pile interaction behavior. The physical model was designed with two piles (with adequate spacing): Pile #1 and Pile #2. Pile #1 is for static-cyclic load test and the Pile #2 is for dynamics load test. A concentrated mass of 323 g was attached to the Pile #2 to represent the superstructure. Figure 2 illustrates both the planned view and three section views of the model, instrumentation and the lateral loading setup. The procedure used in this study is provided in detail in further explanation of this proposed scheme, and that procedure followed in the model construction is described in the next section.

3.2 Model Construction

The first step in the process of constructing the model entailed the creation of a drainage system at the bottom of the container. A drainage tube system was constructed at the bottom (outside) of the container as shown in Figure 3, the base of which was lined with a thin layer (2.5 cm) of gravel to facilitate a uniformly distributed drainage in both the saturation & desaturation process. A filter paper layer was also placed immediately above the gravel layer to control sand flow and to improve the drainage. Pictures of the container with the drainage tube system and the gravel drainage layer are shown in Figures 3 and 4, respectively.

After proper placement of the drainage layer, Ottawa sand was placed using dry pluviation. To obtain a uniform relative density of approximately 45%, a pluviation height of 1cm was employed based on preliminary calibration tests performed prior to the actual model preparation. The surface of each soil layer was leveled using the leveling plank as shown in 5 (b) to place the instruments at the right location. The layer thickness and heights are shown in Figure 2.



All Dimensions are in cm

Figure 2: Plan and three section views of the physical model with instrumentation

When the depth of the soil layer was 9 cm, the model piles were driven into the soil to a depth of 8.5 cm and supported as shown in Figure 5. Also illustrated is the process of sand pluviation (Figure 5a), leveling the surface of each sand layer (Figure 5b), and placement and securing of an accelerometer at the surface of a sand layer (Figure 5c). The sand pluviation and the instrumentation procedures were repeated as summarized in Table 2.

Table 2: Model preparation procedure

Layer #	Soil type	Thickness of the layer, cm	Depth from the top of the box (Z), cm
1	Gravel	2.5	20.5
(Placement of filter paper)			
2	Ottawa Sand	1.5	19
(Placement of water content sensors WC_1, WC_2)			
3	Ottawa Sand	4	15
(Placement of accelerometers A_3, A_4)			
4	Ottawa Sand	3.5	11.5
(Placement of water content sensors WC_3, WC_4, WC_5 and the piles)			
5	Ottawa Sand	3.5	8
(Placement of accelerometers A_5, A_6)			
6	Ottawa Sand	3.5	4.5
(Placement of water content sensors WC_6, WC_7, WC_8 and PPTs PP_1, PP_2) were placed)			
7	Ottawa Sand	3.5	1
(Placement of LVDTs L_1 through L_5 and accelerometers A_7 through A_{10})			

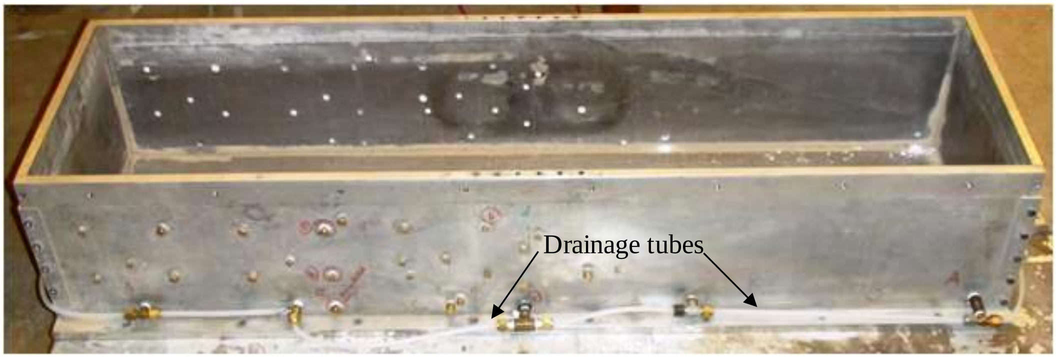
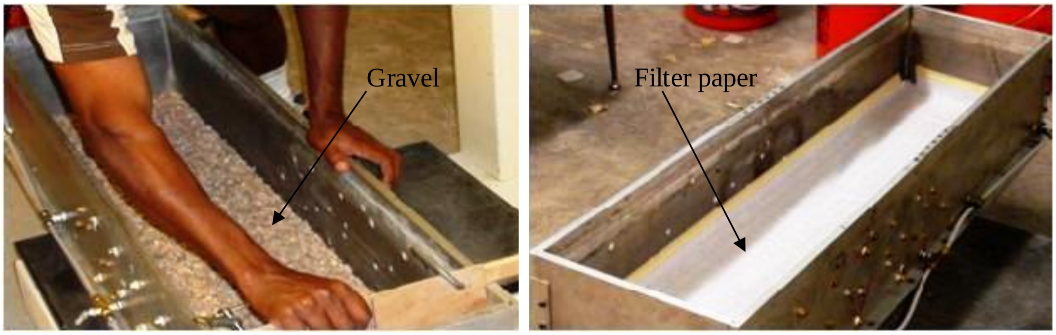


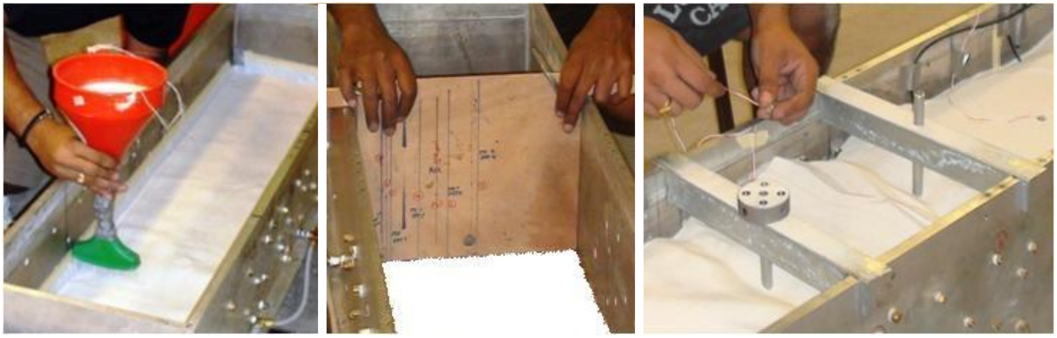
Figure 3: Centrifuge container with drainage tube system

In order to apply a static-cyclic load at the top of the pile, a hydraulic actuator system was attached to a vertical wall of the model container as shown in Figure 6. A load cell and an LVDT were also attached to the system to measure the horizontal load and the corresponding displacement. This horizontal loading setup was controlled remotely from the centrifuge control room.



(a) (b)

Figure 4: (a) Placement of the gravel drainage layer; (b) Placement of the filter layer



(a) (b) (c)

Figure 5: (a) Pluviation of the sand layer; (b) leveling of a soil layer; (c) piles with installation supports and installation of instrumentation

3.3 Preparation of Nozzle System for Steady Precipitation

As explained previously, achieving and maintaining a target degree of saturation profile is a complexity that must be resolved in the centrifuge testing of an unsaturated soil-pile system. The procedure outlined in the previous section was used to provide steady infiltration at the surface of the model. Another important consideration involved the arrangement of the nozzles to obtain uniform infiltration on the plan view. The flow angle of the nozzles and the height above the surface of the model and the flow rate are factors that influence the uniform infiltration. For the centrifuge box used in this study, twelve nozzles were specifically configured to provide a uniform area of coverage. A photograph of the nozzle system with the tubing is shown in Figure 7.

Figure 6: Multiple view of the stepper motor for lateral loading of pile foundation.

(a) (b)

Figure 7: (a) Nozzle system for infiltration application; (b) Test to evaluate flow distribution

3.4 Steps before Spinning

Upon completion of model construction, instrumentation and attachment of lateral loading unit and the nozzle system, the model was carefully transported to the centrifuge bucket and firmly attached to the shake table. The instrumentation, nozzle control and lateral loading control wires were then connected to the data acquisition system. Although there are numerous methods to achieve the target initial degree of saturation, in this study, the model was saturated fully from the bottom of drainage values prior to spinning of the centrifuge. A film of water above the surface of the soil was retained to ensure that the surface did not dry during the initial spinning of the centrifuge. During the saturation process, the saturation tube (see Figure 1) was connected with valve #2 (see Figure 1) while keeping the outflow tank (tank#2) disconnected from the valve #2; the water for saturation was obtained from external water supply system used for saturated tests. While the saturation tank was kept open to the atmosphere, the approximate pressure of 10ft elevation head ensured an adequate flow of water through the model. The saturation process was halted and the saturation tube was disconnected after ensuring that the water level was slightly above the soil surface.

Other requisite concerns requiring resolution prior to achieving and maintaining a uniform degree of saturation entailed either managing or eliminating the evaporation of water from the soil surface during centrifuge spinning. In that the turbulent flow of air in the centrifuge room otherwise dries the soil more rapidly, for the purposes of this study, the model was completely covered with plastic sheets. This elegantly effective yet simple technique reduced the surface evaporation and also prevented water spray external to the model that might cause instrument malfunction. Figure 8 shows the model covered with plastic sheets.

Figure 8: Model covered by plastic sheet

The outflow tank (tank#2 in Figure 1) should be connected with the model to collect the drainage water. In that no flow is possible through a valve if it is closed in the control system, while still remaining physically open, the authors used the control unit to close valve #2, though it was not actually shut. Thusly, the drainage was later activated (during spinning) via the control system. Valve #1 was also closed using the remote control system, while again remaining open physically.

Once the target acceleration is achieved, the drainage system was activated by opening Valve #2 using the control system. The moisture sensor readings were monitored during water draining at a steady flow rate. After acquiring target readings (i.e. target moisture content in the bottom sensor) the spraying process was begun by again opening Valve #1. Both the drainage and the spraying process were adjusted as needed via monitoring of the moisture sensor readings.

4 Sample Results and Discussion

Upon achieving a steady state vertical flow and target degree of saturation (pre-calibrated readings in all moisture sensors), the shaking was applied at the base. The moisture sensor readings (WC1, WC3, and WC6) with depth are shown in Figure 9(a) for two different tests, and the calibration curves for each of these three sensors are shown in Figures 9(c)-(e). Based upon the calibrated curves, the actual degree of saturation was calculated and the variation of degree of saturation with depth is presented in Figure 9(b). Although the measured volumetric water contents do not seem uniform, the degree of saturation profiles seem to be uniform as seen in Figure 9(b) because of different sensors. The first test was performed approximately at 24% average degree of saturation. Although the goal entailed repeating the test at the same degree of saturation, difficulties in achieving identical sensor readings necessitated performing the second test at an approximately 28% average degree of saturation.

The base acceleration time histories applied at the base of the model for Test # 1 and 2 are shown in Figures 10 (a) and 10(c), respectively. The measured horizontal acceleration time histories of Accelerometers A7 and A8 (see Figure 1) are shown for Test # 1 and 2 are shown in Figures 10 (b) and (d), respectively. In that the accelerometer A7 is located away from the piles and the centrifuge box walls, it can be considered as a free-field measurement. The Accelerometer A8 is located close to the dynamic pile, however. Although significant differences were expected in the measured accelerations at A7 and

A8 locations due to dynamic-soil-pile interaction, the differences in the measured accelerations are insignificant. Analogous observations were also made in the Test#2 results. While there are many such reasons for such observations, the amplitude of loading was the primary justification here.

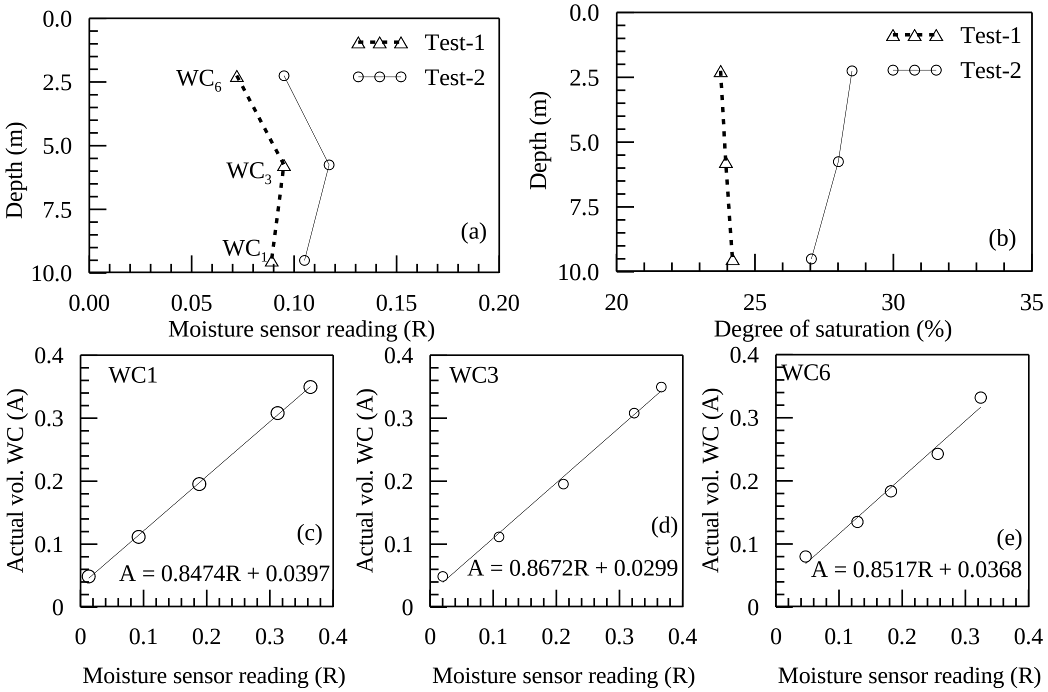


Figure 9: Moisture sensor readings, calibration and profiles

All results within the figures are presented in prototype scale with the maximum spectral value measured in test-2 (approximately 28% degree of saturation) being higher than the maximum spectral value measured in test-1 (approximately 24% degree of saturation). Also the spectral acceleration, calculated (at the surface level) without the SPI influence is slightly higher than the spectral values, calculated upon consideration of the influence of SPI. Based on these analyses, it can be concluded that (i) the degree of saturation influences the response of soil-pile systems; (ii) and that the presence of pile foundation affects the behavior of surrounding soil. Therefore, the standard practice of using free-field ground motion to design the pile foundation should be utilized with caution or must incorporate the soil-pile interaction analysis results. With such a thorough elucidation of the unsaturated soil-pile interaction responses, civil engineers can avoid over-conservative designs accordingly.

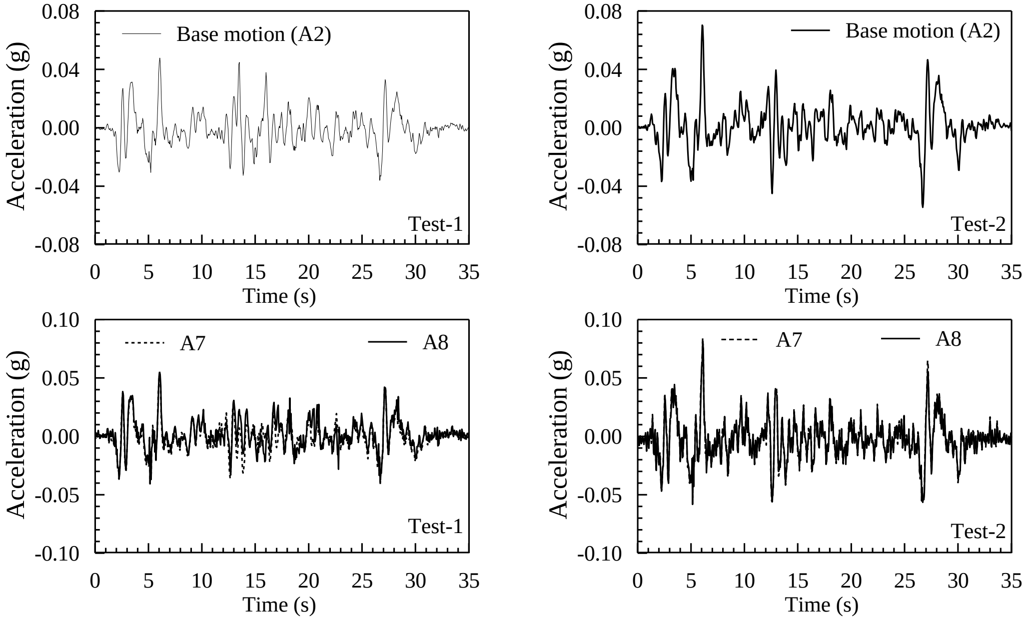


Figure 10: Acceleration time histories of input base motion and measured surface responses close and away from the dynamic pile (Pile # 2)

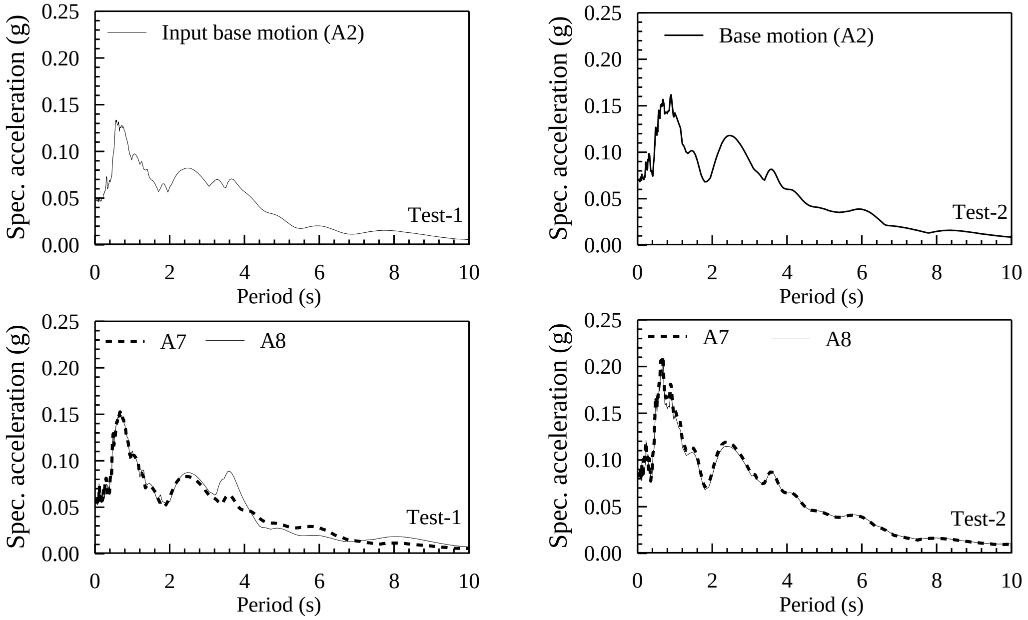


Figure 11: Spectral accelerations of the input base and measured surface responses close and away from the dynamic pile (Pile # 2)

5 Conclusions and Recommendations

In this study, the authors presented, an examination methodology to study the effect of soil degree of saturation on the static and dynamic behavior of unsaturated soil-pile systems using a geotechnical centrifuge. Research results entailing the study of samples of 24% and 28% Ottawa sand are also presented. Because the range of suction variation for sandy soil is small compared to clayey soil, the effect of 4% degree of saturation was insignificant. Nonetheless, the experimental results show to a certain extent, the repeatability of the procedure. The proposed method of spraying water from the top is also relevant for performing more accurate centrifuge modeling with saturated soils without desiccation, which is a problem in long duration spinning. With such direct experience, the authors propose contend that improving the effectiveness of the proposed scheme is possible through the following recommendations.

It is essential to have an buffer layer of soil between the drainage layer and the soil layer of interest. Te degree of saturation of bottom soil layers will remain at near saturation conditions from capillary rise, unless an excellent drainage system is built to avoid such occurrences. A near saturation condition in the bottom layers will create difficulties in achieving a uniform degree of saturation profile with a target degree of saturation. The use of a buffer layer of soil/gravel in between the drainage layer and soil layer under study will thus render negligible concerns about capillary rise. Capillary rise is also reducible by improving the drainage and locating the drainage outlets as low as possible at either the bottom of the model or at the sides.

It is important to ensure that the surface is flat and the water will does flow through weak soil-interfaces. A less than planed soil surface will possibly elicit surface flow, thusly affecting uniformity of infiltration, and subsequently the degree of saturation profile. Furthermore, there is a possibility of weak interfaces formation in the presence of instrumentation wires unless specifically considered. Problems resulting from the proximity of wires can be minimized by routing to the corner of the box and a placing sufficient amount of soil at that respective corner to increase the angle of the slope slightly.

Developing a method to recycle drainage water for spraying purposes is also recommended for increased effectiveness. The limited amount of tanked stored water (Tank #1 in Figure 1) necessitates the reuse and filtering of drainage water (Tank #2 in Figure 1).

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