Impact of Suction on the Near Surface Lateral Soil Response using Centrifuge Modeling

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Abstract. Recent studies have shown that unsaturated soils lead to greater lateral pile capacity. This study aims to experimentally assess how suction stress affects the lateral response of piles in unsaturated cohesionless soil. Two centrifuge tests were performed at 50 g to evaluate the effect of suction stress in the soil. Lateral loads were applied monotonically on a single free-head pile in a displacement-controlled manner to a maximum pile head displacement of 0.44 m. The first test was conducted on fully saturated cohesionless soil, while the second test was performed in an unsaturated state with a mixed unsaturated-saturated soil layer. The water table was lowered to about 0.12 times the embedded pile depth to ensure an unsaturated condition in the zone closer to the surface of the soil. Lateral response assessment indicates that the unsaturated soil influenced the pile head response, leading to larger applied lateral loads for similar pile displacements in comparison to the fully saturated soil test. Experimental findings reveal that suction stress played a meaningful role in magnitudes of pile bending moments and lateral resistances for unsaturated cohesionless soils.

1 Introduction

Unsaturated soils typically exist in areas where the water table is below the soil surface. Previous studies have shown that the behavior of unsaturated soils differs from that of fully saturated conditions due to the effect of the degree of saturation and suction [1–3]. One important parameter that influences the response of unsaturated soil is suction stress [4]. Lu and Likos [5] presented the concept of suction stress in unsaturated soils using the suction stress characteristics curve (SSCC). Their analysis showed that interparticle forces and forces related to the macroscopic stress in unsaturated soils all contribute to suction stress magnitudes. Furthermore, the suction stress could be estimated from the known unsaturated soil parameters such as matric suction, volumetric water content, and the degree of saturation, among others.

Numerous studies have also incorporated unsaturated soil mechanics in the geotechnical analysis of various problems, such as in situ testing, seismic response of foundations, and the analysis of retaining structures, to mention a few [6–9]. Komolafe and Ghayoomi [10] recently incorporated suction stress in the determination of the theoretical ultimate lateral resistance of cohesionless soils. Their results showed that the lateral resistance in sandy soils could increase up to 100% by lowering the water table level, emphasizing the effect of unsaturated soils on pile lateral behavior.

Pile lateral response has been an area of interest over the years [11–13]. Experimentally, strain gauges are typically installed along the pile to obtain displacement, bending moment, and lateral resistance profiles to depict the lateral behavior of piles. A common approach used to evaluate the lateral soil-pile interaction is the p-y curve method. The original p-y curve approach in sands was developed by Reese et al. [14] in 1974 and later modified for use offshore by the American Petroleum Institute [15]. However, there is a need to extend the application of the p-y curve method through the inclusion of unsaturated soil mechanics by considering suction stress impact in the lateral response of piles in sand. In this paper, the results of a centrifuge test on a single free-head pile installed in cohesionless soil are presented to evaluate the impact of suction stress on lateral soil-pile interactions near the soil surface. Comparisons are made for the fully saturated soil and a mix of the unsaturated-saturated soil layer condition. Then, the results are discussed in terms of soil-foundation measures, and insights for future research are provided.

2 Materials and methods

2.1 Experiment Setup

A physical modeling system was designed to test a single laterally loaded pile foundation inside a 5 g-ton geotechnical centrifuge at the University of New Hampshire (UNH), which has been utilized in similar research studies [2,16,17]. Soil layers were prepared in a soil box container with internal dimensions of 356 mm in length, 178 mm in width, and 254 mm in depth. The tests on the model pile were conducted at 50g, corresponding to the middle of the embedded pile depth for the prototype

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scale. A loading actuator incorporated with a linear variable differential transformer (LVDT) was placed on the free-head pile to apply lateral loads on the pile up to a maximum pile head displacement of 0.44 m. Additionally, various sensors such as pore water pressure transducers (PPTs) and dielectric sensors were installed in the soil to monitor the degree of saturation in the soil as the water table was lowered from the fully saturated state. Also, an LVDT was placed on the soil surface to determine how much the soil settled during centrifuge spin-up. A schematic showing the cross-section of the model setup in the rigid soil box is depicted in Fig. 1.

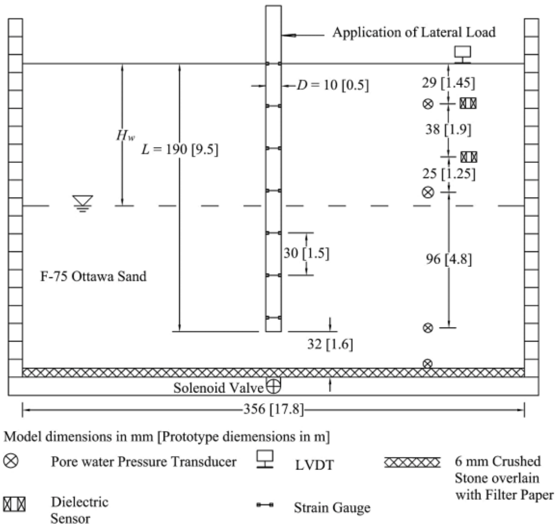


Fig. 1. Schematic of the centrifuge model pile setup.

2.2 Soil Material and Preparation

The soil used for this study was the F75 Ottawa sand. Based on the Unified Soil Classification System, the soil is classified as poorly graded sand. The particle size distribution of the soil is shown in Fig. 2, and a summary of the soil properties is also provided in Table 1.

The soil specimen in the setup was prepared using dry pluviation with a soil hopper of a 4 mm diameter opening. First, 6 mm crushed stone aggregates overlain with a double ply of light tracing cloth paper (considered as a filter paper) were placed at the base of the soil box container to allow for ease of water flow beneath the soil and reduce upward piping. The soil was then prepared in lifts of 25 mm up to 32 mm from the base of the box. The pile was placed carefully on the soil surface and held at the center of the soil box container using a clamp. Afterward, the soil was prepared around the pile up to the required height to achieve a wished-in-place pile installation. The prepared soil sample was fully saturated and carefully mounted in the centrifuge.

For the unsaturated soil test, the water table was lowered after the centrifuge was spun to 50g (corresponding to the mid-depth of the embedded pile shaft) and monitored to the desired level using the PPTs. The soil sample has fine particles with relatively high permeability and can hold up water to a suction of 10 kPa.

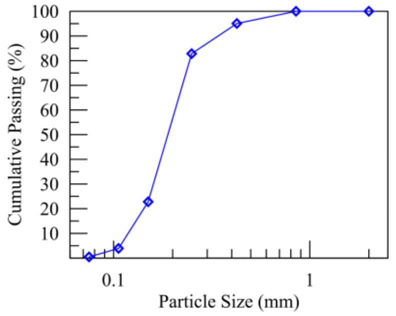


Fig. 2. Particle size distribution of F75 Ottawa sand.

Table 1. Summary of soil properties.

Soil Parameter	Value
Coefficient of uniformity, C_u	1.767
Coefficient of curvature, C_c	1.032
Specific gravity, G_s	2.65
Void ratio, e	0.604
Minimum and maximum void ratios, e_{min}, e_{max}	0.49, 0.80
Friction angle (degrees), ϕ	36
Residual volumetric water content, θ_r	0.07
Residual degree of saturation, S_r	0.2
van Genuchten parameter, n	9
van Genuchten parameter, α	0.25

Expressions for the determination of the degree of saturation (S), suction stress (σ_s), and effective vertical stress ($\sigma_v{}'$) are shown in Equations 1 to 3 [4,5,18],

$$S = S_r + [1 + \{\alpha(u_a - u_w)\}^n]^{\frac{1-n}{n}}(1 - S_r) \quad (1)$$

$$\sigma_s = -(u_a - u_w)[1 + \{\alpha(u_a - u_w)\}^n]^{\frac{1-n}{n}} \quad (2)$$

$$\sigma_v{}' = \sigma_v - u_a - \sigma_s \quad (3)$$

where $(u_a - u_w)$ is the matric suction, σ_v is the total vertical stress, and u_a is the pore air pressure which could be taken as equal to zero under field conditions. Experimental soil water retention characteristics from previous research on the soil material used for this study were used to fit the soil water retention curve (SWRC) shown in Fig. 3 using van Genuchten fitting parameters [19,20].

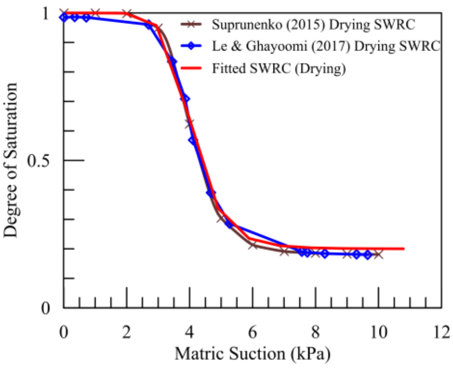


Fig. 3. SWRC of the F75 Ottawa sand.

2.3 Scaling Effects

Evaluating the effects of centrifuge scaling is important in modeling the soil-pile system. For ease of evaluating various scaling effects, the prototype scale will henceforth be used to describe the soil-pile interactions.

One important concept that needs to be considered in centrifuge modeling is the boundary effect the soil container has on the assessed structure. Zhu et al. [21] suggested that to reduce the boundary effect on a model pile, the distance between the pile shaft and the inner walls of the soil box container should be a minimum of $7D$ (3.5 m). The distance between the pile shaft and the inner walls of the container in this study is 4.2 m, thus satisfying the boundary effect criterion.

Grain size effect is another centrifuge modeling criterion that cannot be ignored. Ovensen [22] recommended that the ratio of the pile diameter to the average grain size of the soil should be greater than 30,

$$D/d_{50} > 30 \tag{4}$$

where D is the diameter of the pile, and d_{50} is the average grain size of the soil. The D/d_{50} for this study is 53, which satisfies the requirement for grain size effect considerations.

A number of studies have also assessed the effect of roughness in centrifuge modeling [23,24]. In this study, the pile shaft was abraded to remove specks of dirt and cleaned thoroughly with acetone. Strain gauges were mounted at the required sections on the pile, and then the pile was coated with a layer of M-Coat A air-drying polyurethane to protect the strain gauges.

2.4 Soil-Pile Lateral Interaction

A steel pile of prototype diameter $D = 0.5$ m with a prototype embedded pile length $L = 9.5$ m was used for the testing program. Table 2 provides a summary of the pile properties. The pile lateral behavior was assessed using its slenderness ratio $L/D = 19$. According to Higgins et al. [24], the pile can be classified as semi-rigid. Hence there may be a transition from rigid to flexible behavior as the pile displaces laterally due to increasing lateral load.

Table 2. Properties of the laterally loaded pile

Parameter	Value
Diameter, D (m)	0.5
Embedded pile length, L (m)	9.5
Young's modulus, E_p (GPa)	200
Yield stress, σ_y (MPa)	350
Plastic moment, M_p (kN.m)	7292
Bending stiffness, EI (kN.m²)	613592

Soil-pile interaction of a laterally loaded pile is simulated with a series of elastic springs along the depth of the pile following the Wrinkler model. The reaction of the elastic springs has a direct influence on the bending moment of the pile. Ignoring the axial forces and weight of the pile, the solution of the laterally loaded pile problem along the pile depth (z) results in a differential equation given as

$$EI\frac{d^4y}{dz^4} + E_s y = 0 \tag{5}$$

where EI is the pile bending stiffness, y is the pile lateral displacement, and E_s is the soil modulus.

Thus, the lateral resistance (or soil reaction) p along the pile can be expressed as

$$p = -E_s y = EI\frac{d^4y}{dz^4} \tag{6}$$

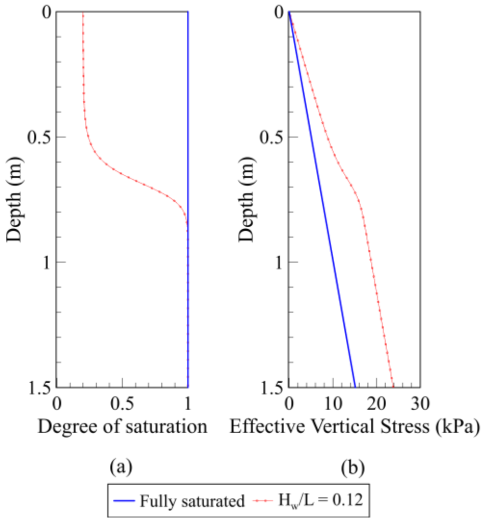
Likewise, the profile of the bending moment M along the pile shaft can be obtained using

$$M = EI\frac{d^2y}{dz^2} \tag{7}$$

where $\frac{d^2y}{dz^2}$ is the bending curvature obtained from the strain gauges installed along the embedded pile length, as shown in Fig. 1. Lateral resistance was obtained as a double derivative of the bending moment profile using the derivative method, which involves using forward finite differences at each strain gauge location and the point of loading on the pile head. However, lateral displacement along the pile shaft was obtained from the double integral of the bending curvature profile using pile head boundary conditions of slope $(\frac{dy}{dx})$ and displacement (y) at the point of lateral loading application. The fifth-degree polynomial adequately fitted the bending curvature profile from the centrifuge tests and was employed in obtaining the lateral displacement profile [25].

2.5 Testing Program

Results of two centrifuge tests are presented to assess the influence of suction stress on the pile lateral response. The tests were conducted by applying lateral load monotonically in a displacement-controlled manner at the pile head using a loading rate of 0.02 mm/s, thus simulating gradual pile failure. The degree of saturation and effective vertical stress profiles for the near soil surface up to a depth of 1.5 m are shown in Figs. 4(a) and 4(b). Furthermore, a summary of the tests conducted is shown in Table 3.



(a) (b)

Fig. 4. Profiles based on the SWRC for (a) degree of saturation; (b) effective vertical stress

Table 3. Centrifuge testing program

Test ID	Water Depth, H_w (m)	Effective Stress at 1.5 m (kPa)
Fully Saturated	0	15.14
$H_w/L = 0.12$	1.09	23.83

3 Analysis of Results and Discussions

In this section, lateral response analyses based on the results from the fully saturated and unsaturated soil centrifuge tests were assessed in terms of displacement, bending moments, and lateral resistance.

Fig. 5(a) shows the displacement response of the pile along its normalized depth (z/L) when loaded to a maximum pile head displacement of 0.44 m. The results indicate that similar lateral displacements were observed along the embedded pile shaft for both tests. This suggests that the unsaturated soil did not substantially influence the lateral displacement response for the displacement-controlled tests since the pile did not exhibit flexible behavior.

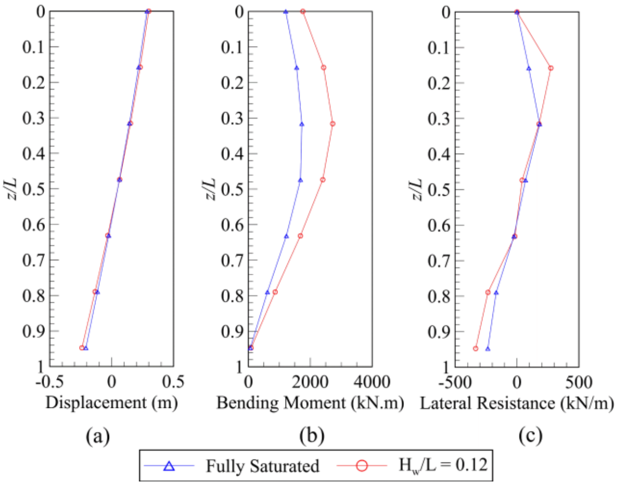


Fig. 5. Lateral response along the pile shaft (a) displacement; (b) bending moment; (c) lateral resistance

However, Fig. 5(b) revealed that at the maximum pile head displacement, larger bending moments were experienced along the embedded pile length for the unsaturated test due to increased soil stiffness in the upper layer of the soil as a result of suction stress. Peak bending moments were observed close to a depth of about 0.3 times the embedded length of the pile for both tests. Magnitudes of peak bending moment at the maximum pile displacement for the unsaturated test indicate a 58% increase from the fully saturated condition, thus showing that the influence of suction stress on the flexural behavior of the pile is significant. In Fig. 5(c), higher lateral resistances were observed for the unsaturated test at depths closer to the ground surface due to the increased effective stress in the unsaturated soil zone. The peak lateral resistance for the fully saturated test was observed to occur slightly deeper from the ground surface as a result of lower effective stress when compared to the unsaturated test.

Assessment of the pile head response is one of the direct approaches to evaluating the lateral behavior of a pile. The load-displacement response was obtained at the pile head using the load actuator mounted in the centrifuge chamber. Incorporated into the load actuator were an LVDT for measuring the lateral displacement at the pile head and a load cell for measuring the applied lateral loads. Pile head slope measurements were obtained using a camera installed on the loading frame and perpendicular to the point of load application. Images from the camera were further processed using WebPlotDigitizer [26].

Results from the pile head and maximum bending moment response are shown in Figs. 6(a) to 6(d). The pile head response in Figs. 6(a) and 6(c) show that the degree of saturation in the soil directly influences how much load the pile experiences when it is loaded in a displacement-controlled manner. Higher lateral loads were required at the maximum pile displacement for the unsaturated test than the test on the fully saturated soil. Specifically, the lateral load required to mobilize the fully saturated soil to a pile head displacement of 0.44 m was 320 kN, while that of the unsaturated soil was 509 kN, thus indicating a 59% change in applied lateral load between the two saturation conditions.

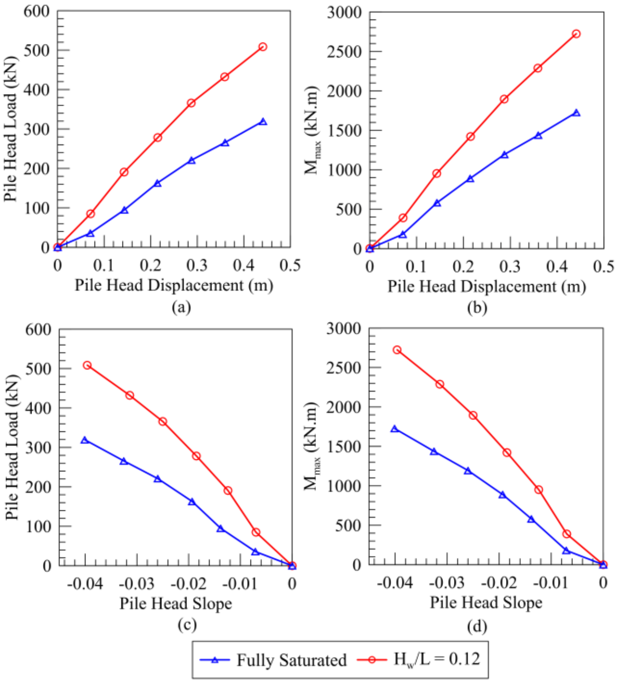


Fig. 6. (a) Pile head load-displacement response; (b) maximum bending moment-displacement response; (c) pile head load-slope response; (d) maximum bending moment-slope response

The results obtained were consistent with those from existing studies. For example, results from Mahmood et al. [27] indicated that at similar pile head displacements, lateral loads on the pile in unsaturated soil conditions were greater than those of the fully saturated or dry soil conditions due to the effect of matric suction on the soil. Also, Lalicata et al. [28] compared the effect of the unsaturated soil on the pile head response based on soils with different void ratios, and they observed that the higher stiffnesses induced above the water table were due to the increase in the effective mean stress in the unsaturated soil. Thus, larger lateral loads were experienced for the test having the saturated-unsaturated soil mix. Figs. 6(b) and 6(d) exhibit the mobilization of the maximum bending moment along the pile shaft (M_{max}) with the lateral displacement and pile head slope, respectively. The results are identical in trend to those observed for the pile head response, thereby indicating a close correlation between the applied lateral loads and the maximum bending moment

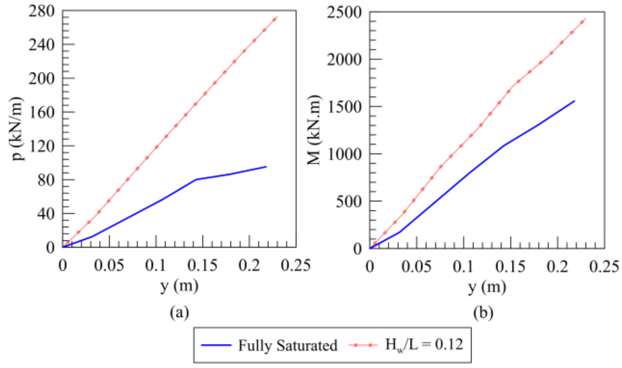


Fig. 7. Lateral soil-pile interaction at 1.5 m (a) p-y curves; (b) M-y curves

The p-y curve results in Fig. 7(a) show that the lateral resistance for the fully saturated soil was lower than that of the unsaturated test at any given displacement. For the unsaturated soil test, suction stress significantly affected the failure wedge mobilized in front of the pile as it displaced laterally, leading to greater values of lateral resistance on the p-y curves. The results were consistent with those of Lalicata et al. [29]. They observed that the lateral resistances along the p-y curve showed an increasing trend in the unsaturated soil condition but were closer to steady lateral resistance values for the fully saturated soil at similar values of lateral displacements.

Fig. 7(b), on the other hand, shows the mobilization of the bending moment on the pile near the soil surface to investigate the effect of the capillary zone on the lateral soil-pile interaction. Results from the analysis show a substantial increase in bending moment when the water table in the soil was lowered, thus showing that increased capillarity due to suction stress would lead to higher bending moments. The trend of the results in Fig. 7(b) was also quite similar to those observed in Fig. 6, indicating that the influence of the unsaturated soil was significant at the 1.5 m depth. Furthermore, the results show that the moment-displacement response could also adequately describe the lateral soil-pile response.

Fig. 8 reveals the impact of the unsaturated soil on the mobilized lateral resistance at a depth of 1.5 m from the soil surface. Normalized lateral displacement at the soil surface with respect to the pile diameter was represented as y_o/D. The effective stress at 1.5 m for the unsaturated test was 23.83 kPa, and for the fully saturated test was 15.14 kPa. Results show that as the pile displaced laterally, the lateral resistances mobilized during the unsaturated test were significantly more than those observed for the fully saturated test. This trend can be attributed to the influence of suction stress which increases the effective stress in unsaturated soil conditions, while in the fully saturated state pore water pressure reduces the effective stress. Hence, suction stress influenced higher mean effective stress and, consequently, greater mobilized lateral resistance.

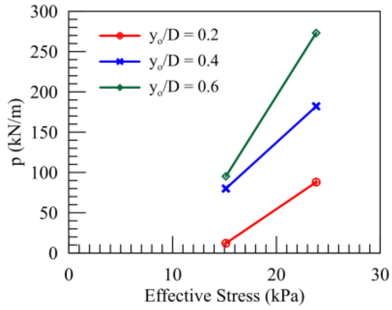


Fig. 8. Effect of the unsaturated soil on lateral resistance at 1.5 m below the soil surface

4 Conclusions

Two centrifuge experiments were performed at 50g to investigate the impact of suction stress on the lateral response of a single free-head pile. Comparisons of results were made for the fully saturated soil and an unsaturated condition ($H_w/L = 0.12$). The pile was loaded in a displacement-controlled manner up to a maximum pile head displacement of 0.44 m. Analysis of results revealed that suction stress increased the effective stress in the unsaturated soil zone, thus, leading to greater soil stiffness in the unsaturated soil test with a mix of unsaturated and saturated soil layers. This phenomenon led to greater pile bending moments and lateral resistance for the unsaturated soil test. Furthermore, larger pile head lateral loads and maximum pile bending moments were observed in the unsaturated soil test owing to the impact of suction stress on the soil-pile lateral response.

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