SINGLE PILES AND PILE GROUPS CAPACITY IN UNSATURATED SANDY CLAY BASED ON LABORATORY TEST

by Heni Pujiastuti

SINGLE PILES AND PILE GROUPS CAPACITY IN UNSATURATED SANDY CLAY BASED ON LABORATORY TEST

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Abstract

Pile capacity is one of the controlling factors in the foundation design. Before the model piles were subjected to the compression and uplift loading, it is required to carry out experimental study on the model piles driven into sandy clay set in a test box. The diameter of single-pile concrete models was 16 mm, with ratios of 6, 10, 15 and 20 for pile length (L) to diameter (d). The diameter and length of concrete pile group models were 10 mm and 200 mm, respectively, with four different configuration groups, i.e., single pile, two piles (2×1), three piles (triangle), and four piles (2×2). The sandy clay was prepared in three different water contents of 17.40%, 23.44%, and 27.86%. The study found which the single piles and pile groups capacity subjected to uplift load were smaller than those under compressive load. Increasing the pile length to the ratio of diameter (L/d) and matric suction resulted in increased capacity of single piles subject to uplifting and compressive loads. The pile groups' capacity depended on both the matric suction and the pile number in a group. The pile groups' compressive capacity in a condition of unsaturated soil (within the matric suction of soil 73.67 kPa) increased by 294.96%-346.39% than in saturated soil conditions (within the matric suction of soil 2.727 kPa).

Keywords: Compressive load, Degree of saturation, Matric suction, Pile foundation, Uplift load

Introduction

In engineering practices, the design of pile foundation driven into unsaturated soil uses the saturated soil parameters, which assume the weakest soil conditions. The use of saturated soil parameters ignores the parameters of matric suction that give significant effect on the pile capacity. Unsaturated soil is found above groundwater levels (vadose zone), semi-arid region, and arid region. Its pores contain water and air, which lead to two types of pore pressure in its elements, i.e., pore air pressure (u_a), and pore water pressure (u_w), in which their difference is known as matric suction [1]. Soil pore water's thermodynamic potential impacts the importance of matric suction [2]. The changes in the degree of saturation affect the soil's shear strength as well as the water content and the soil's matric suction [3].

Besides its significant impact on both the soil shear strength as well as the pile capacity, the presence of the vadose zone above the groundwater level also contains the potential danger of collapsing upon being wet. The gravimetric water content expresses the amount of water in the soil, as well as volumetric water content and the degree of saturation[4]. The soil water characteristic curve expresses the hydromechanical behavior of unsaturated soil, defining the relation between soil water quantity and matric suction in [5, 6].

Researchers [7-9] have conducted various experimental and semi-empirical methods that accentuate the important impact of soil matric suction on increasing soil shear strength. Furthermore, [8, 10, 11, 12] published the equations of shear strength using semi-empirical methods to determine unsaturated soil shear strength utilize the soil-water characteristic curve (SWCC) as well as the parameter for saturated soil shear strength.

Generally, the pile foundation used to support the building or move the superstructural burden into the hard soil [13, 14]. Application on the field shows that it usually works as a group of piles. The single pile behavior due to a load applied to it is different from the group of piles' action. Interaction effect between the piles occurs in pile group, but not in the single pile. Researchers have conducted studies focused on experimental, analytical, and computational models on the impact of soil matric suction on a pile of foundation action under unsaturated soils [15-17].

Al-Omari et al. [15] conducted observation of the capacity of the group of piles pushed into unsaturated and saturated clay based on laboratory experiments. Study results state the pile group capacity increases in line with the pile number increase. Such increasing pile capacity under soil condition of unsaturated is higher than under soil condition of saturated since, respectively, they increase nonlinearly and linearly.

The behavior of the pile foundation in unsaturated sandy clay by using the analytical methods was observed by Pujiastuti et al. [16]. In line with the increasing soil matric suction, end bearing efficiency, friction capacity, and total capacity are increasing non-linearly. For small matric suction, the skin friction value tends to be higher than the end-bearing capacity value. Whereas in certain matric suction, the values tend to be constant and increase, respectively. In the overall matric suction observed, the total pile capacity increases significantly.

The pile foundations that modeled small was tested on unsaturated clayey soil using the finite-element method to restrain static axial loads. The results of the loading test on the pile and the finite element method were compared [17]. Based on finite element method analysis results, the typical pattern of the load and pile head settlement relationship indicates an acceptable consistency to the results of the loading test on the pile. Increasing soil water content and decreasing matric suction lead to decreasing shear strength, consequently, diminishing the pile's ultimate capacity.

This paper performed experimental tests on unsaturated soil to obtain the soil's physical and mechanical properties. The tensiometer was used in the test box to calculate the matric suction. To determine the impact of pile length to diameter ratio to the model piles capacity were carried out the loading tests on the pile models. The influence on the pile number in a group, the saturated/unsaturated soil conditions, the compressive/uplift loading also were observed. The loading tests conducted on the pile models were driven into sandy clay, which static compacted.

Material, Experimental Model and Testing Program

Soil

Yogyakarta, Indonesia, took the soil sample, 40% clay, and 60% sand mixed. Table 1 describes the soil's physical and mechanical characteristics. The undrained cohesion, as well as the friction angle of soil, were obtained from the Unconsolidated Undrained Triaxial test. The hydromechanical behavior of sandy clay with the air entry value (AEV) and the residual suction value (*Sr*), as shown in Figure 1. The measuring result of the tensiometer instrument was the matric suction data used for plotting the SWCC.

Table 1 The soil's physical and mechanical characteristics

Soil properties	Value	Unit
Undrained cohesion, c_u	50.46	kPa
Friction angle of soil, ϕ	17.74	°
Air Entry Value, AEV	28.06	kPa
Residual suction value, *Sr*	210.00	kPa
Specific Gravity, *Gs*	2.62	
Soil fraction (ASTM):		
- clay (0.005 to 0.001 mm)	9.88	%
- silt (0.075 to 0.005 mm)	51.85	%
- sand (2 to 0.075 mm)	38.27	%
Plasticity Index, PI	14.76	%
Plastic Limit, PL	21.24	%
Liquid Limit, LL	36.00	%
Soil classification :	CL (USCS) A6 (AASTHO)	

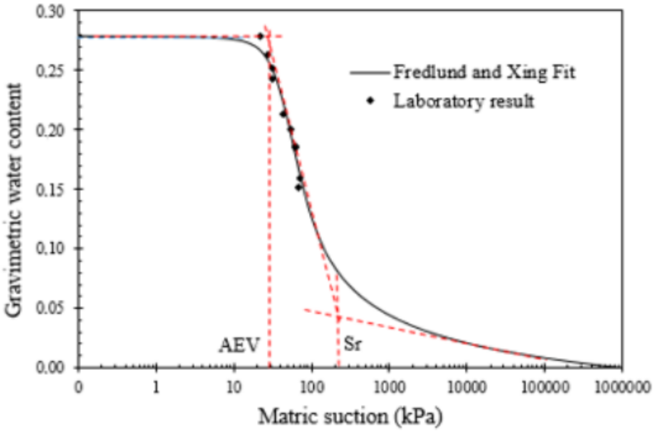

Figure 1. The hydromechanical behavior of sandy clay

Water content utilized for soil compaction in the test box determined the soil saturation. The plan's water content difference for unsaturated conditions was respectively 23.44% and 17.40%. Meanwhile, the water content for the saturated condition was determined at 27.86%. The results of matric suction measurements by using the tensiometer instrument in the test box for the 17.36%, 23.41%, and 27.82% water content were 73.67 kPa, 53.61 kPa, and 2.727 kPa, respectively.

Test Box and Set-Up Loading

Laboratory tests were conducted on the model pile in the test box. Figure 2 describes the setting up of compression and uplift loading test for single pile and pile group models. The test box consisted of steel plate with 9.5 mm thickness and 40 × 60 × 5 mm hollow steel section (HSS) as the frame and stiffeners to form a test box in 110 × 110 × 110 cm dimension. The material used to make the test box was estimated to endure the frame reaction due to the loading test. The tarpaulin was used to cover the inside of the test box so that the surface of the box was waterproofed and smooth. It was also used for reducing the contact between the test box surface and the soil. More details related to experimental test equipment have been reported by Pujiastuti [18].

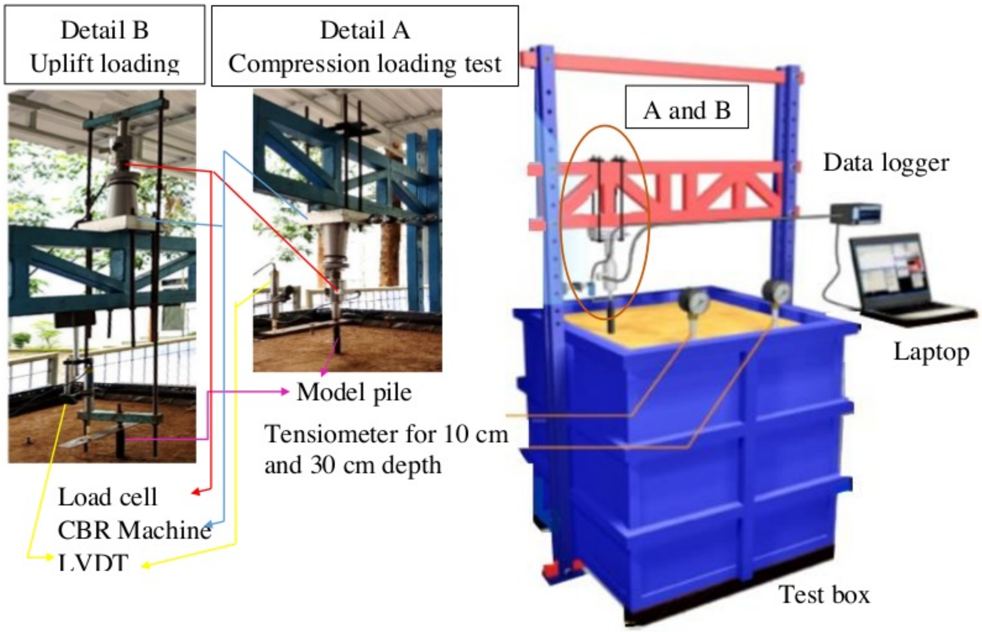

Figure 2. The test set up for the model pile under compression loading test (Detail A) and uplift loading test (Detail B)

The diameter ratio of soil media (*D*) and the model pile (*d*) was determined to be larger than eight or $D/d > 8$ in order to avoid the influence of soil media limitations [19]. Furthermore, to avoid negligible scale effects, the pile diameter applied in this study was larger than $20 \times D50$ (size of soil grain). The influence zone of the soil was 3–8 times of the pile diameter [20]. Gaaver [13] has set the limit the diameter of soil media for the model pile to be 12 times and 8 times of the pile diameter for horizontal direction and vertical direction, respectively.

Pile Caps and Model Piles

The single pile models were made of cylindrical concrete with an outer diameter (*d*) of 16 mm, pile length (*L*) of 96 mm, 160 mm, 240 mm and 320 mm with the *L*/*d* ratios of 6, 10, 15 and 20 as shown in Figure 3. While the pile-group models were made of 10 mm outer diameter (*d*) cylindrical concrete, the pile-length (*L*) was 200 mm with a *L*/*d* ratio of 20. The caps were created from a 15 mm thick steel plate. The pile group models were varied in the number of piles, i.e., one, two, three, and four piles in a group. The distance between piles was 2.5*d*, as shown in Figure 4. The upper part of the pile cap was provided with a connection for the uplift load.

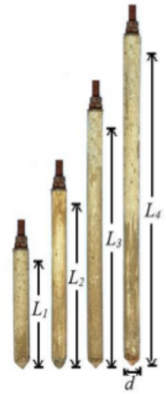

Figure 3. Variation of single pile model with different length: L_1= 96 mm; L_2= 160 mm; L_3= 240 mm; L_4= 320 mm and the same of pile diameter: d= 16 mm

Figure 4. Pile group's model variance, different pile arrangement, and the similar pile length and diameter: L= 200 mm; d= 10 mm

Experimental Model

For a few days, The field sample of soil was dried with aerated, pulverized, and filtered with #10 sieve (sieve hole diameter 2 mm) before being combined with water at predefined water content. In this observation, three variations of water content were applied, i.e., 17.40%, 23.44%, and 27.86%. Until being processed for one day, the ready soil-water blend was put tightly closed plastic bags assure uniform water quality in the sample. It should be noted that the sandy clay-water mixture (hereinafter referred to as soil) was prepared in ten layers put inside the test box at a thickness of about 100 mm. The soil was put inside the test box and then compacted with a manual compactor. For all layers in the test box the compaction method was consistent. Instead, the core cutter test was taken after the soil was compacted per layer to assess the soil's density. The average of dry soil density in the test box was 95% of the maximum dry density of the result of the Proctor compaction with the standard method.

The model piles were driven into 200 mm depth before subjected to axial compression and uplift load. For the pile group models, in particular, the pile cap was mounted with bolts on the pile end afterward, before the burden was adjusted to it. The tests set up for both single pile and pile group models were similar to Figure 2. The compression and uplift load were applied with a constant rate of penetration method. A pile penetration rate of 0.85 mm/minute was referred to ASTM D1143-81 [21] for the compression load and ASTM D3689-90 [21] for the uplift load.

During compression/uplift load test the load applied and the pile head displacement were registered. The linear variable displacement transducer (LVDT) was mounted on the head of the pile to calculate the pile displacement. The 30-WF6209 LVDT with a stroke length of 50 mm was utilized in this study. This model was supplied with a spring-loaded shaft, subject to the location being extended to the maximum. The accuracy of LVDT readings was 0.01 mm. The load cell 28-WF6453 was utilized to calculate the compression and uplift load applied at the head of the pile. The accuracy of load cell readings was 0.01 kg. LVDT and the load cell was connected with a 30-WF6016 Geodatalog series 6000 data logger to collect and record data before being processed in the laptop computer. The operating range for the tensiometers used to calculate matric suction in the test program was 0 to 100 kPa.

Testing Program

The planning of test was built to assess the behavior of the pile groups and single piles driven into sandy clay where the compressive and uplifting load was applied. This research also considered differences in the pile length to the ratios of diameter (*L*/*d*), degree of soil saturation and the pile number in a group.

Twenty-four tests on the single pile models were conducted. The following information are four test sets conducted on single pile models with uplift load, and four compressive load test sets. The single-pile models given with both tests indicated variations in the ratio of 5, 10, 15, and 20 pile length to diameter (*L*/*d*). Each pile model was driven into three variations of soil water content, i.e., 17.36% and 23.41% (for unsaturated soil conditions), and 27.82% (for saturated soil condition). Under the determined water content, the degrees of saturation values of above-mentioned pile models were 62.31%, 84.02%, and 99.85%, respectively and the matric suctions of soil were 73.67 kPa, 53.61 kPa, and 2.727 kPa respectively.

For the pile group models twenty-four tests were also conducted. In detail, four sets of uplift load and compressive load tests were given to the pile group models, which showed variations of piles in the group, i.e., Single Pile (SP), Two Piles (2PG), Three Piles (3PG), and Four Piles (4PG); with a center-to-center distance of 2.5*d*. Each pile group model was driven into three variations of soil water content, i.e., 17.36% and 23.41% (for unsaturated soil conditions), 27.82% (for saturated soil condition).

From each compressive test, load and settlement data were obtained and in the uplift test, the load and displacement data were measured. The data was used to plot the relationship between load-settlement and load-displacement. The pile's ultimate bearing capacity was determined either directly from the charts, or using the method of double tangent.

Result and Discussion

Single Pile Capacity

Single Pile Under Uplift Load

Typical relationships between displacement and uplift capacity are shown in Figure 5 in various *L*/*d* ratio of the single pile driven into sandy clay at 84.02% degree of saturation. In general, the uplift capacity-displacement responses of any pile were similar. Figure 5 indicated a progressive increase in the uplift capacity in line with the increasing ratio of *L*/*d*.

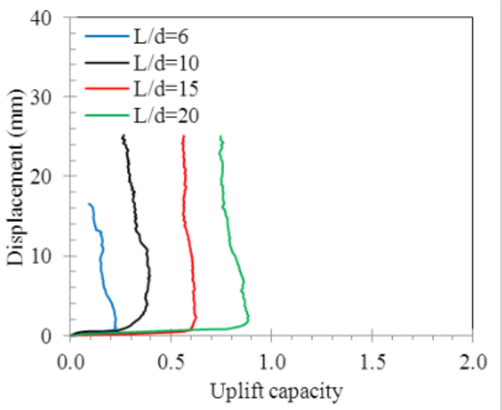

Figure 5. Single pile uplift capacity versus displacement under the different ratio of *L*/*d*

The ratio length of the pile to the diameter, as well as the degree of saturation, affected the single pile's uplifting capacity, as shown in Figure 6. It can be observed that the single pile's ultimate uplifting capacity significantly increased in consequence of an increase in the ratio of *L*/*d* and the transition from saturated to unsaturated soil conditions. These increased ultimate single-pile uplift capacity could be due to three different factors. The first was the pile, as well as soil improved frictional resistance. When the depth of pile embedding increased, so was the effective stress at the pile's mid-height. As a result, the friction resistance was improved. The second was the increasing area of contact the pile, as well as soil due to the rising depth of pile embedding. The third was the increasing matric suction under the saturated to unsaturated condition. Such increase of matric suction would decrease the contacted area of soil particles due to water meniscus. Then, the continuous water phase was also reduced due to the air entering into the soil pores that increased the friction between particles (inter-particle force). Consequently, the strength of soil shear and resistance to pile-soil friction would be increased. Increasing the single pile uplift capacity in unsaturated soil (with 84.02% and 62.31% degree of saturation) to the individual pile uplift capacity under saturated conditions (with 99.85% the degree of saturation) were 154.84%–164.71% and 184.03%–195.29%, respectively.

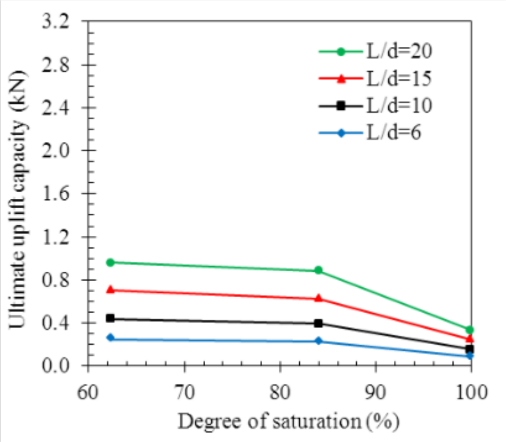

Figure 6. Ultimate uplift capacity for single pile versus degree of saturation of soil under different *L/d* ratio

Single Pile Under Compressive Load

Figure 7 shows typical relationships between settlement and compressive capacity of the single pile in various *L/d* ratio driven into sandy clay with 84.02% degree of saturation. In general, the compressive capacity-settlement responded to all of the piles were relatively similar. The test results indicated significant increase of compressive capacity in *L/d* ratio of 20. It was observed that the compressive capacity was higher than the uplift capacity. The compressive load adjusted to the pile was later accepted as pile capacity for skin friction, which was recognized at first by the friction resistance of the pile. Furthermore, after achieving certain settlement, the end bearing pile capacity was then mobilized. Meanwhile, the uplift load applied to the pile showed resistance that only came from the pile of skin friction.

Such as in Figure 8, the pile embedding depth to diameter ratio, as well as the degree of soil saturation, affected the ultimate compressive capacity of the single pile. The transition from saturated soil conditions (99.85% degree of saturation) to unsaturated soil conditions (84.02% and 62.31%) resulted in an essential increase in the compressive capacity of the single pile on all variation of *L/d* ratio. The transition of soil conditions (from saturated to unsaturated) and the friction between particles (inter-particle force) increased as matric suction increased. This induce an improvement in the shear strength of the unsaturated soil, pile-soil friction resistance, and end-bearing pile. The higher *L/d* value caused greater pile end bearing and soil-pile friction resistance. In line with the rising pile embedment depth, the contact area between the soil-pile and the end bearing capacity increased.

Such factors led to an improvement in the compressive capacity of the single pile driven into unsaturated soils, which was consistent with the increasing depth of the pile embedding. Increasing the single pile compressive capacity in unsaturated soil (with the degree of saturation of 84.02% and 62.31%) to the single pile compressive capacity under saturated conditions (with the degree of saturation of 99.85%) were 241.90%-333.33% and 366.43%-561.11%, respectively.

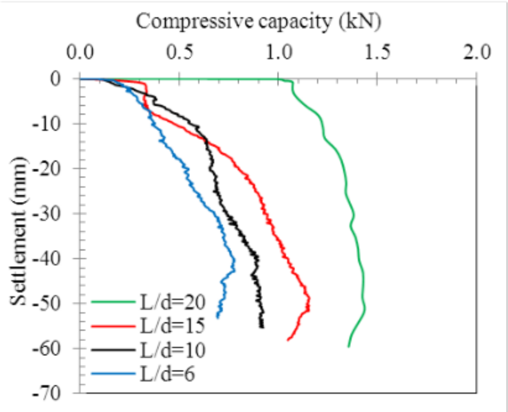

Figure 7. Compressive capacity for single pile versus settlement under different *L/d* ratio

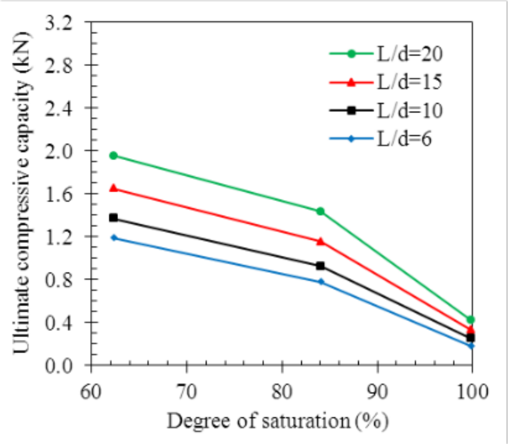

Figure 8. Ultimate compressive capacity for single pile versus degree of saturation of soil under different *L/d* ratio.

Pile Group Capacity

Pile Group Under Uplift Load

The relation between the pile group displacement and the uplift capacity with a different pile number in a group and the 84.02% degree of soil saturation shown in Figure 9. In general, the relationship between uplift capacity and displacement responses in all the pile groups were relatively similar in their shapes. Figure 9 indicates, the capacity of uplift risen according to the rising pile number in a group.

As seen in Figure 10, the degree of saturation and the pile number in a group influenced the pile groups'ultimate capacity. It was found, the pile group's uplift capacity risen significantly inline the rise in the pile number in a group as well as the transition (from saturated to unsaturated) soil conditions. This can be related to two different factors. Due to the confinement effect, the first factor was increased friction resistance between soil and pile. The effect of soil confinement was created through the presence of several piles well into the pile group. Furthermore, the soil became solid as well as increased the friction resistance in line with the pile. The confinement effect created the pile-soil block. The degree of pile-soil block flexibility depended on the rigidity of the caping pile framework as well as the overlapping structures [22]. The second factor was the increase of matric suction because of the transition of soil conditions (from saturated to unsaturated), as discussed in the preceding paragraph for the single pile. These two factors led to increasing single pile uplift capacity-driven into unsaturated soils, which was in line with the increasing pile number in a group. Increased pile group uplift capacity under unsaturated soil (with 84.02% and 62.31% degree of saturation) to the pile group uplift capacity under saturated conditions (with 99.85% degree of saturation) were 245.04%-271.34% and 431.68%-490.06%, respectively.

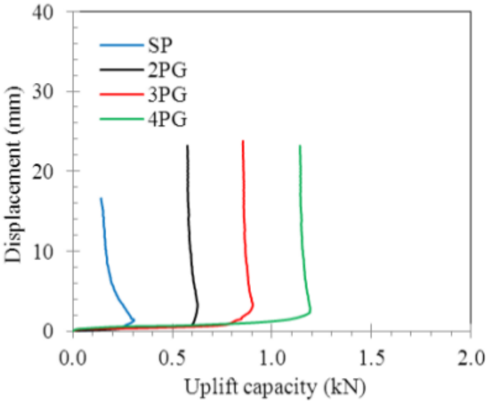

Figure 9. Uplift capacity for the pile group versus settlement under different the pile number in a group

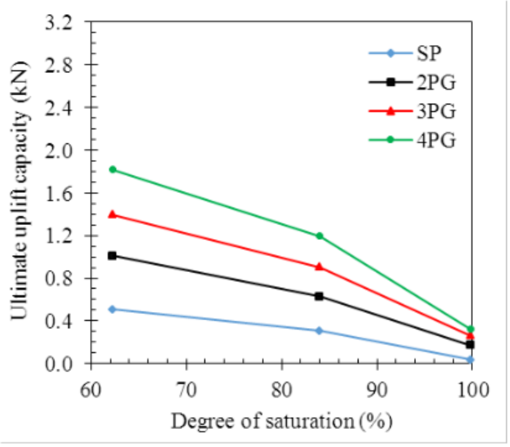

Figure 10. Ultimate uplift capacity for the pile group versus the degree of saturation

Pile Group Under Compressive Load

Figure 11 shows the typical relationships between settlement and compression capacity of the pile group-driven into sandy clay and the different numbers of the pile in a group and the degree of soil saturation of 84.02%. The observation results indicated a progressive increase of compressive capacity in line with the increasing pile number in a group.

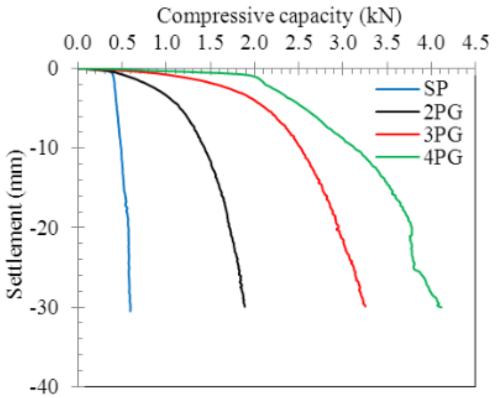

Figure 11. Pile group compressive capacity versus the settlement under various pile number in a group

Figure 12 shows the relationship of the pile group's ultimate compressive capacity, the pile number within the group and the saturation degree.It is shown which the compressive capacity was greater than the pile group's uplift capacity. Besides the soil conditions, the pile number in the group has influenced the pile group's ultimate compressive capacity, as shown in Figure 12. It can be noticed that the transition of soil condition (from saturated to unsaturated) and the confinement effect generated the increasing pile-soil friction resistance as well as the pile group end bearing. The increasing of the pile group compressive capacity under unsaturated soil (with 84.02% and 62.31% degree of saturation) to the pile group compressive capacity under saturated conditions (with 99.85% degree of saturation) were 228.57%–298.91% and 294.96%–346.39%, respectively.

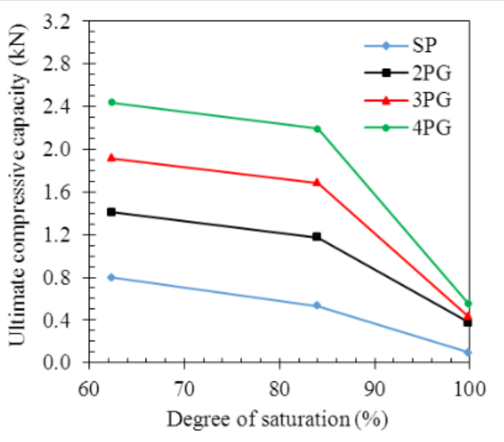

Figure 12. The pile group's ultimate compressive capacity versus degree of soil saturation

Conclusion

The matric suction had a significant effect on both soil shear strength and pile bearing capacity. The design of pile foundation under unsaturated soil was usually conducted using saturated soil parameters, which ignored the matric suction parameter. There had been various experimental tests on an individual pile and group models of piles consisting of two, three, and four piles. The pile models were driven into unsaturated and saturated compacted sandy clay, before subjected to the uplift and compressive loads.

The results indicate that the single pile and pile group capacity under the compressive load was higher than under the uplift load. The single pile actions depended mainly on the soil conditions and the ratio of pile embedding depth with a diameter and under compressive and uplifting load. Single piles' capacity under compressive and uplifting load increased significantly in line to the increasing *L/d* ratio and soil's matric suction. The pile groups' capacity under the compressive and uplift load increased in line with the increasing pile amount of piles in a group as well as a matric suction of soil.

Acknowledgments

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ORIGINALITY REPORT

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