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

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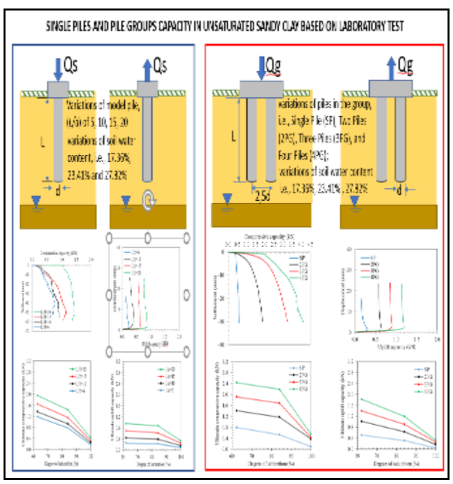
Graphical abstract



Abstract

Pile capacity is one of the controlling factors in the foundation design. In this study, compression and tension tests were carried out on model piles driven in sandy clay in a test box. The diameter of concrete single-pile 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 capacities of the single piles and pile groups 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 (with the matric suction of soil of 73.67 kPa) increased by 294.96%-346.39% when compared to those in saturated soil conditions (with the matric suction of soil of 2.727 kPa).

Keywords: Compressive load, degree of saturation, matric suction, pile foundation, uplift load

1.0 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, $(u_a - u_w)$[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 utilizing the soil-water characteristic curve (SWCC) as well as the parameter for saturated soil shear strength.

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

Based on laboratory experiments, Al-Omari et al. [15] observed that the capacities of group piles in unsaturated soils increases at higher rates than those in saturated soils which linearly increases with the number of piles. Based on analytical studies of piles in unsaturated sandy clay, Pujiastuti et al. [16] reported that end bearing capacity, friction capacity, and total capacity nonlinearly increased with the increase of soil matric suction. Under small matric suction, the skin friction tends to be higher than the end-bearing capacity value. However, the skin friction tends to be constant whereas the end bearing capacity increases as the matric suction increases. In the overall matric suction observed, the total pile capacity increases significantly.

A small-scale pile model on unsaturated clayey soil simulated to resist static axial loads using the finite element method. The results of the numerical analysis were compared with the results of the pile load test, have been carried out by [17]. The results show that the general trend of the relationship of pile load and pile head settlement obtained by the numerical analysis shows a good consistence with the pile load test results. The increasing of soil water content and the decreasing of matric suction lead the shear strength decrease, and consequently the ultimate bearing capacity of pile decreases.

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.

2.0 METHODOLOGY

2.1 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.

Table 1 The soil's physical and mechanical characteristics

No.	Soil properties	Value	Unit
1	Undrained cohesion, c_u	50.46	kPa
2	Friction angle of soil, ϕ	17.74	°
3	Air Entry Value, AEV	28.06	kPa
4	Residual suction value, *Sr*	210.00	kPa
5	Specific Gravity, *Gs*	2.62	
6	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	%
7	Plasticity Index, PI	14.76	%
8	Plastic Limit, PL	21.24	%
9	Liquid Limit, LL	36.00	%
10	Soil classification :	CL (USCS) A6 (AASTHO)	

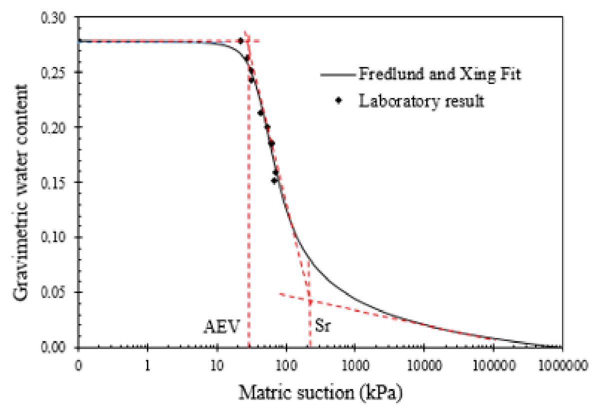


Figure 1 The hydromechanical behavior of sandy clay

Based on the relationship between the degree of saturation and water content, the saturated soil sample was prepared by compacting in a test box using the water content of 27.86%. The unsaturated samples were prepared using the water contents of 23.44% and 17.40%. The matric suction measured by a tensiometer in the test box for the water contents of 17.36%, 23.41%, and 27.82% were 73.67 kPa, 53.61 kPa, and 2.727 kPa, respectively.

2.2 Test Box and Set-Up Loading

Laboratory tests were conducted on the model piles in a test box. The setups of compression and uplift loading tests for single pile and pile group models are shown Figure 2.

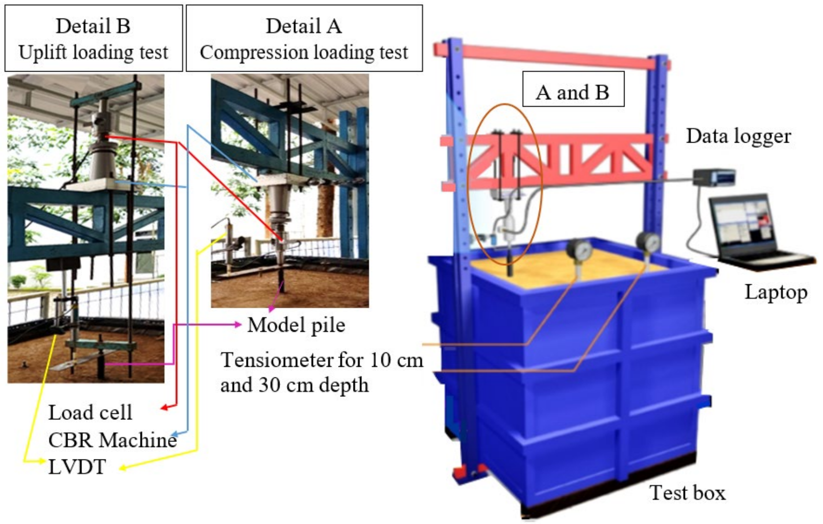


Figure 2 Setups of model piles for compression and uplift loading tests [18]

The test box consists of with 9.5 mm steel plate and 40 × 60 × 5 mm hollow steel section (HSS) as frames and stiffeners. The dimensions of the test box are 110 × 110 × 110 cm (width × length × height). The inside of the box was covered by a tarpaulin for reducing the contact between the test box surface and the soil. Details of the test equipment have been reported by Pujiastuti [18].

The diameter ratio of soil (*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 scale effects, the pile diameter applied in this study was larger than 20 × *D50* (size of soil grain). The influenced zone of the soil was 3–8 times of the pile diameter [20]. Gaaver [13] has set the limit diameters of soil media for a model pile to 12 times and 8 times of the pile diameter for horizontal direction and vertical direction, respectively.

2.3 Pile Caps and Model Piles

The single pile models were made of cylindrical concrete with an outer diameter (*d*) of 16 mm, pile lengths (*L*) of 96 mm, 160 mm, 240 mm and 320 mm with the *L/d* ratios of 6, 10, 15 and 20 (see 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.

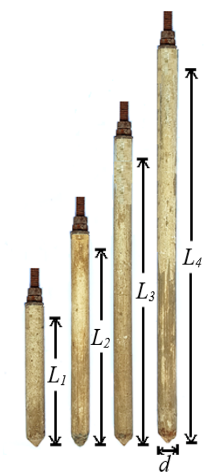


Figure 3 Single pile models: L_1= 96 mm; L_2= 160 mm; L_3= 240 mm; L_4= 320 mm, *d*= 16 mm

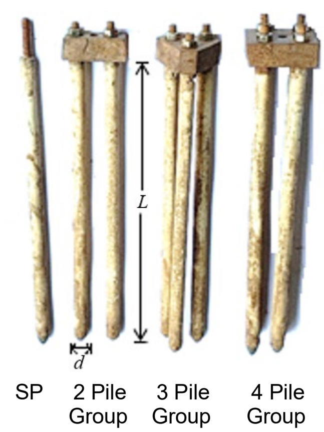


Figure 4 Group pile models: *L*= 200 mm; *d*= 10 mm

2.4 Experimental Model

A field sample soil was dried for a few days, then, aerated, pulverized, and filtered with a #10 sieve (sieve hole diameter 2 mm) before combined with water at predefined water contents of 17.40%, 23.44%, and 27.86%. The ready soil-water blend was stored in tightly closed plastic bags and then stored for 1 day to assure uniform water content in the sample. The sandy clay-water mixture (hereinafter referred to as soil) was prepared in ten layers inside the test box at a thickness of about 100 mm. Each layer was consistently, compacted by a manual campactor and sampled by a core cutter for density tests. The average relative compaction of soils in the test box was 95% with respect to the standard Proctor tests.

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

During compression/uplift loading tests, the load applied and the pile head displacement were registered. The linear variable displacement transducer (LVDT) has a stroke length of 50 mm and an accuracy of 0.01 mm. The load cell 28-WF6453 has an accuracy of 0.01 kg. The 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 of the tensiometers used to calculate matric suction in the test program was 0 - 100 kPa.

2.5 Testing Program

The tests were arranged for investigating the influences of the pile length, the degree of soil saturation and the number of piles in a group.Twenty-four tests on the single pile models were conducted. The following information are four test sets of uplift and compressive load tests on single pile models with the length-to-diameter ratio (*L/d*) of 5, 10, 15, and 20.

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.

3.0 RESULTS AND DISCUSSION

3.1 Single Pile Capacity

3.1.1 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*.

The length to the diameter ratio, 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 *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 causes the area of the water meniscus which is in the contact area between soil particles to decrease. 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 the degree of saturation of 84.02% and 62.31%) to the individual pile uplift capacity under saturated conditions (with the degree of saturation of 99.85%) were 154.84%–164.71% and 184.03%–195.29%, respectively.

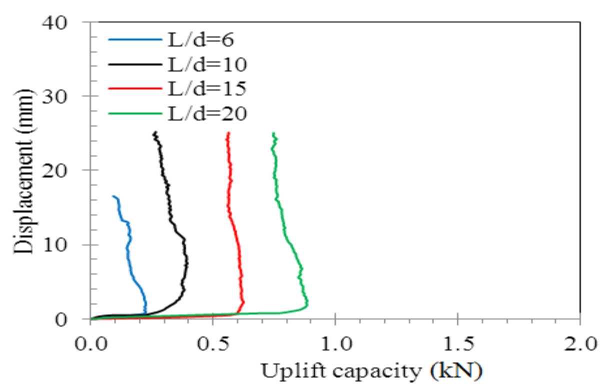


Figure 5 Single pile uplift capacity versus displacement under the different ratio of *L/d*

3.1.2 Single Pile Under Compressive Load

Figure 7 shows typical relationships between settlement and compressive capacity of the single pile driven into sandy clay with 84.02% degree of saturation. In general, the compressive capacity-settlement responses of the piles were relatively similar except the case of *L/d* of 20 which shows significantly stronger than the others. 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.

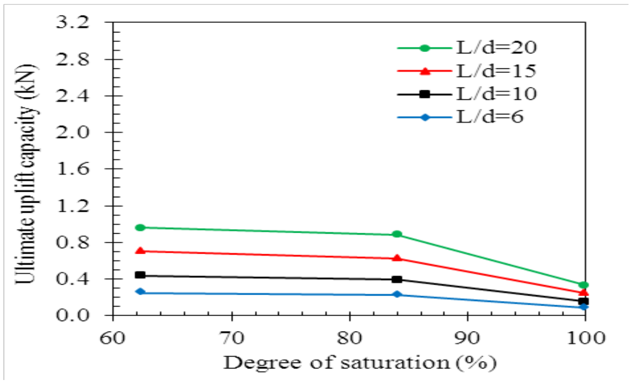


Figure 6 Ultimate uplift capacity for single pile versus degree of saturation of soil under different *L/d* ratio

Such as in Figure 8, the length to the diameter ratio, as well as the degree of saturation, affected the single pile compressive capacity. As in a single pile that is subjected to uplift load which has been discussed above, the transition from saturated soil conditions to unsaturated soil conditions, the compressive load resulted in an increase in the single pile compressive capacity on all variations of *L/d*. The transition of soil conditions causes the increase in matric suction and the friction between particles, pile-soil friction resistance, and end-bearing pile. In line with the rising pile embedment depth, the contact area between the soil-pile and the end bearing capacity increased. 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.

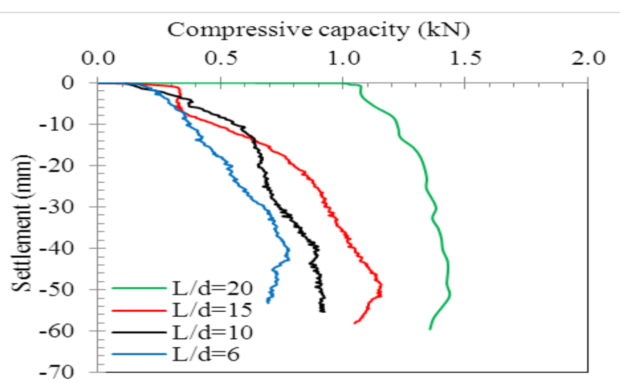


Figure 7 Compressive capacity for single pile versus settlement under different *L/d* ratio

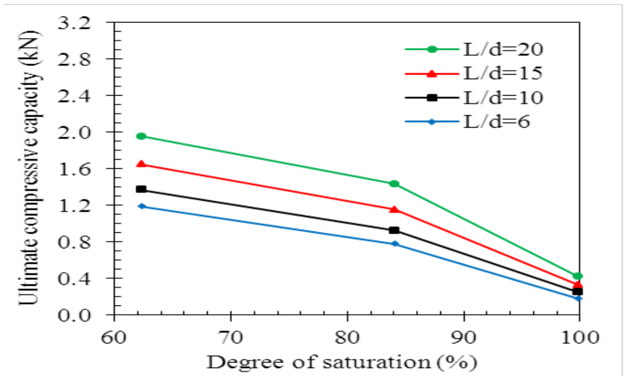


Figure 8 Ultimate compressive capacity for single pile versus degree of saturation of soil under different *L/d* ratio.

3.2 Pile Group Capacity

3.2.1 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.

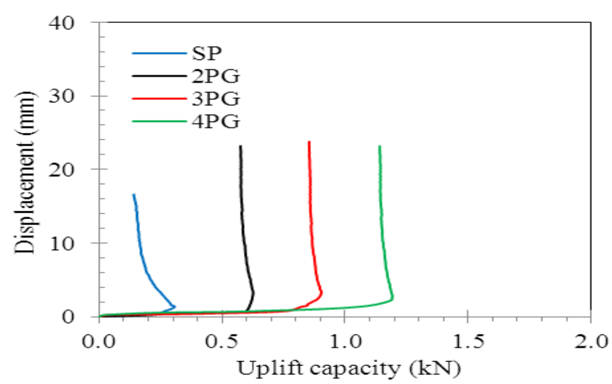


Figure 9 Uplift capacity for the pile group versus settlement under different the pile number in a group

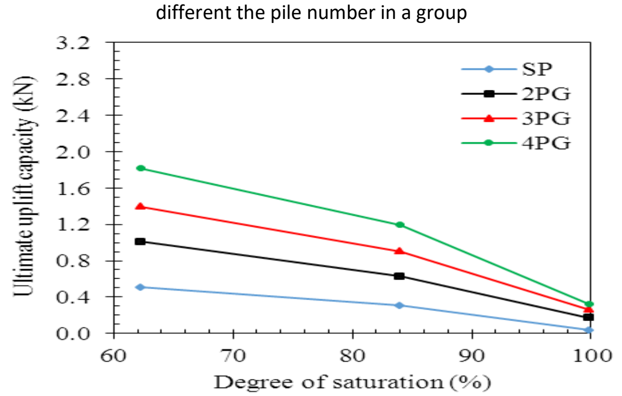


Figure 10 Ultimate uplift capacity for the pile group versus the degree of saturation

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. The first factor was increased friction resistance between soil and pile, due to the confinement effect. 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 the degree of saturation of 84.02% and 62.31%) to the pile group uplift capacity under saturated conditions (with the degree of saturation of 99.85%) were 245.04%-271.34% and 431.68%-490.06%, respectively.

3.2.2 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.

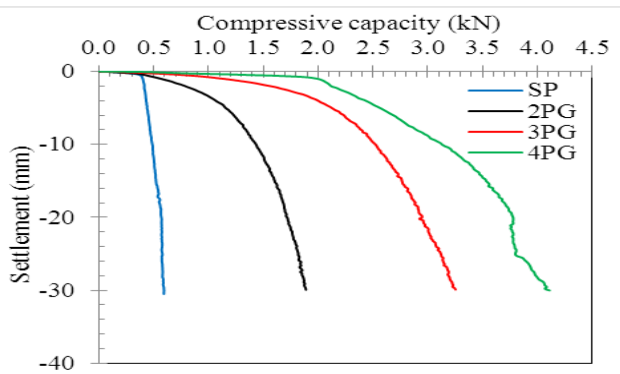


Figure 11 Pile group compressive capacity versus the settlement under various pile number in a group

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.

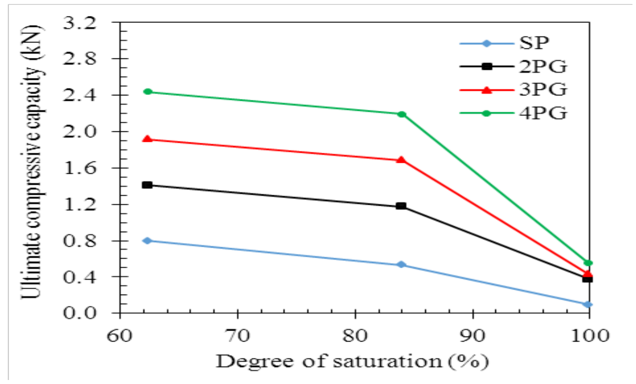


Figure 12 The pile group's ultimate compressive capacity versus degree of soil saturation

4.0 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.

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