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BEHAVIOR OF BEARING CAPACITY ON PILE FOUNDATION DURING FLUCTUATING GROUNDWATER LEVEL

*Sutasinee Intui[1], Suttisak Soralump[2] and Shinya Inazumi[3]

[1]Graduate School of Engineering and Science, Shibaura Institute of Technology, Japan;
[2] Faculty of Engineering, Kasetsart University, Thailand;
[3] Department of Civil Engineering, Shibaura Institute of Technology, Japan

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ABSTRACT: The recent decrease in the groundwater level in the Bangkok area has mainly occurred due to inappropriate water pumping for industrial and agricultural activities. This inappropriate pumping is not only causing land subsidence but is also affecting the load capacity of the soil around the piles. At present, the groundwater level in the Bangkok area is showing a tendency to increase to the ground surface thanks to the reduction in groundwater pumping. This is an important issue of research into the soil load capacity behavior around piles with changes in the groundwater level. This study focuses on the bearing capacity behavior of a single pile by comparing the results of centrifuge tests and the results of previous studies. The test results are compared for each groundwater level. Finally, the results of the tests are summarized into two parts. The first part is that the bearing capacity of the soil around the pile is related to the changing groundwater level but inversely. The soil strength is seen to decrease as the groundwater level increases or rises to the ground surface. The bearing capacity in clay mainly depends on the consolidation process. The second part is that the results of the pile load behavior from the centrifuge tests tend to be like those of the previous studies. Therefore, centrifuge test results can be used to evaluate and design pile foundations in the Bangkok area with changing groundwater levels.

Keywords: Bangkok clay, Centrifuge test, Bearing capacity, Settlement, Groundwater

1. INTRODUCTION

At present, most constructions in soft soil areas use pile or deep pile foundations. The type of pile is chosen by the characteristics of each construction, the type of building, and the load of the structure. Thus, the bearing capacity is the most important factor to analyze in terms of pile performance. The significant parameters affecting the pile capacity are the groundwater level and the soil characteristics.

Bangkok and its vicinity are located in a soft soil area that used to be part of the sea. The soil profile shows alternating layers of sand and clay from soil deposits. The first soil layer is a top clay crust with a thickness of 1 to 2 meters from the ground surface. The second soil layer is a very soft to soft clay layer with a thickness of about 14 meters. The third soil layer is a medium-stiff to very stiff clay layer, extending to a depth of about 25 meters, followed by a medium dense sand layer, referred to as the first sand layer, extending to a depth of 40 meters. The deeper layers comprise alternating layers of stiff clay and dense sand, reaching great depths that have very high soil strength.

In terms of the groundwater situation in Bangkok, the groundwater level changes in the quantity of groundwater pumping. The Department of Groundwater Resource evaluated the groundwater level by installing piezometers at many stations [1]. The results showed that the groundwater level was drawn down to the minimum level around 1997 due to groundwater pumping. Then, a decrease in the groundwater pumping rate led to the recovery of the groundwater level to the ground surface. The groundwater level is presently recovering to the ground surface thanks to monitoring at piezometer stations in Bangkok and its vicinity.

Much research has been done on the strength of the Bangkok area soil. The strength and stiffness of Bangkok clay have been monitored at Sukhumvit MRT Station using the PLAXIS 3D model to compare the hardening soil model and the Mohr-Coulomb model [2]. The results revealed that the Bangkok clay characteristics of the hardening soil model were better than those of the Mohr-Coulomb model for excavation work. The numerical model proved that the results of the hardening soil model can be employed to analyze and predict the ground surface settlement in both 2D and 3D analyses. A comparison of the load capacity between barrette piles and bored piles at similar depths found that barrette piles, with dimensions of 1.5x3.0 meters and a depth of 57 meters, have a higher bearing capacity than bored piles in Bangkok, Thailand [3].

Additionally, the bearing capacity of the two types of piles is not different. Thus, that research recommends barrette piles for high pile capacity designs. On the contrary, the soil strength estimated through a numerical method showed that the positive skin friction value of barrette piles is more than that of bored piles [4]. The strength of soft Bangkok clay was measured using the recompression and SHANSEP techniques [5]. The results of their comparison of the undrained shear stress values showed that recompression tests yield higher values than those estimated from the SHANSHEP technique by about 28%. Finally, the research proved that the corrected field vane shear tests match the SHANSHEP triaxial data well. Additionally, the undrained shear strength of the MRT blue line project and the MRT blue line extension project, Bangkok, Thailand was examined [6]. Their research used a single pile with a diameter of 1.5 meters and a length of 55 meters. The results revealed the undrained shear strength of stiff clay of about 40 to 100 kN/m^2 by triaxial tests and the undrained shear strength of soft clay of about 10 to 50 kN/m^2 by vane shear tests. The development of negative skin friction was found on piles driven into soft Bangkok clay [7]. This research showed that the undrained shear strength values of medium-stiff to stiff clay and sand are 3 to 8 t/m^2 and 18 to 25 t/m^2, respectively, by direct shear tests (DSs), field vane shear tests (FVs), Dutch Cone tests (DCs), and Ko consolidated undrained triaxial tests (CKoU). The results of the pile load tests conducted in the Bangkok area by driven piles and bored piles have been summarized. For the stiff clay layer, the undrained shear strength is 200 to 250 kN/m^2 by unconfined compression tests and standard penetration tests, and the average skin friction is about 100 kN/m^2 [8].

It is important to consider the groundwater level in constructions since the bearing capacity of the soil affects the safety of the structures. This is because the water level, in terms of the pore water pressure, will reduce the soil strength. The present research shows the results of centrifuge tests performed during the recovery or rising of the groundwater level. The results were verified with the data from the previous research by the authors [9]. Thus, this research will show the bearing capacity of a single pile while the groundwater level changes from the surface and then experiences groundwater level drawdown due to water pumping until the recovery of the groundwater level to the ground surface.

2. RESEARCH SIGNIFICANCE

The groundwater level has many effects on infrastructure especially structures located in soft soil areas. This research focuses on the bearing capacity of a single pile during groundwater level change in the Bangkok area, Thailand. Groundwater level change has directly affected the bearing capacity because the soil strength around the single pile depends on pore water pressure and soil characteristics. This research proved that the groundwater level is the main factor in the bearing capacity of both the clay and sand layer. So, the authors hope this research can help researchers and engineers to understand and estimate the soil strength during groundwater level change.

3. METHODOLOGY

This research focuses on the bearing capacity behavior of a single pile and attempts to model a single pile while changing the groundwater level at different intervals. The centrifuge tests were divided into three stages for one model to represent a bored pile under the impact of engineering structures during the changes in groundwater level using geotechnical centrifuge tests done at Hong Kong University of Science and Technology [10].

2.1 Model preparation

2.1.1 Load distribution

The soil strength theory depends on many parameters, such as the soil layers, soil properties, and groundwater level. Following the previous study [3], this research chooses two soil layers to represent the soil condition in the Bangkok area for the model because they have a very high load transfer. Following Fig.1, the load distribution refers to the percentage of load transfer to each soil layer of the barrette and bored piles. Most of the load is transferred to the medium dense sand layer, followed by the hard clay layer and then the stiff clay layer.

2.1.2 Soil model

Following the capacity of the soil from the previous study, medium dense sand and stiff clay were chosen for this research to simplify the model preparation and to represent the Bangkok soil profile that has alternating layers of clay and sand. Even though the hard clay layer has the 2nd highest percentage of load transfer for both types of piles, it is almost impossible to prepare this layer to attain the density of the hard clay layer in the centrifuge model. Thus, Kaolin clay and Toyoura sand were used as stiff clay and medium dense sand, respectively. The Speswhite Kaolin clay was prepared at a water content of 27%, a density of 1.65 t/m^3, and undrained shear strength of 35 kPa. The Toyoura sand was prepared with a controlled density of 1.53 t/m^3. A summary of the soil model is given in Table 1 to Table 3.

Table 1 Properties of Toyoura sand

Properties	Value	Unit
Mean diameter, D_{50}	0.17	mm
Maximum void ratio, e_{max}	0.977	-
Minimum void ratio, e_{min}	0.597	-
Specific gravity, Gs	2.65	-
Dry density, γ_d	1.73	t/m^3
Effective angle of friction at critical	31	degree

Table 2 Properties of Speswhite Kaolin clay

Properties	Value	Unit
Specific gravity	2.65	-
Liquid limit, LL	46	%
Plasticity limit, PL	24	%
Silt	0	%
Sand	31	%
Clay	69	%

Table 3 Properties of stiff Bangkok clay

Properties	Value	Unit
Specific gravity	2.74	-
Liquid limit, LL	46±2	%
Plasticity limit, PL	19±2	%
Silt	23	%
Sand	43	%
Clay	34	%

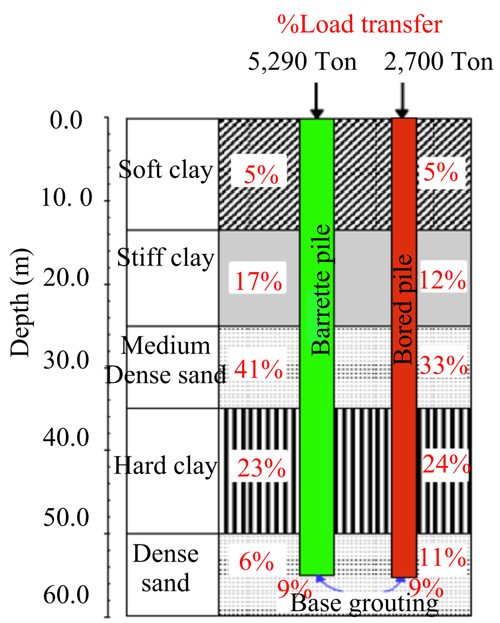

Fig.1 Percentage of load transfer to each soil layer in pile load tests.

2.1.3 Water flow system

The water flow system in the centrifuge tests was modeled by installing a standpipe at the bottom of a strongbox. A standpipe is a PVC tube covered with a geotextile. The end of the standpipe was connected to a hole in the strongbox and a reservoir or water tank next to the strongbox. This system was installed to control the water level at each stage of the tests, as mentioned previously.

2.1.4 Single pile model

The model for the single pile was an aluminum tube equipped with strain gauges. The dimensions of the model pile are a diameter of 2.4 meters (30 mm for the pile model) and a length of 50.4 meters (630 mm for the pile model). Wheatstone bridge strain gauges were installed at seven levels in the pile to measure the values of the pile movement during testing. The aluminum tube was divided into six segments because doing so would make it easy to install the strain gauges inside the pile segments. To prevent the electric circuit installed in each segment from water, the tape was wrapped around the circuit to protect it, as shown in Figs.2 and 3. After connecting the pile segments, the pile model was coated with a thin layer of liquid epoxy to form a watertight layer.

2.1.5 Bored piles

Three bored piles were installed in the model to perform a pile load test at each water level. The diameter of the pile was 2.4 meters and the length was 50.4 meters. The three single piles were installed in the strongbox, as shown in Fig.4.

Fig.2 Strain gauges by full Wheatstone bridge circuit

Fig.3 Single pile model

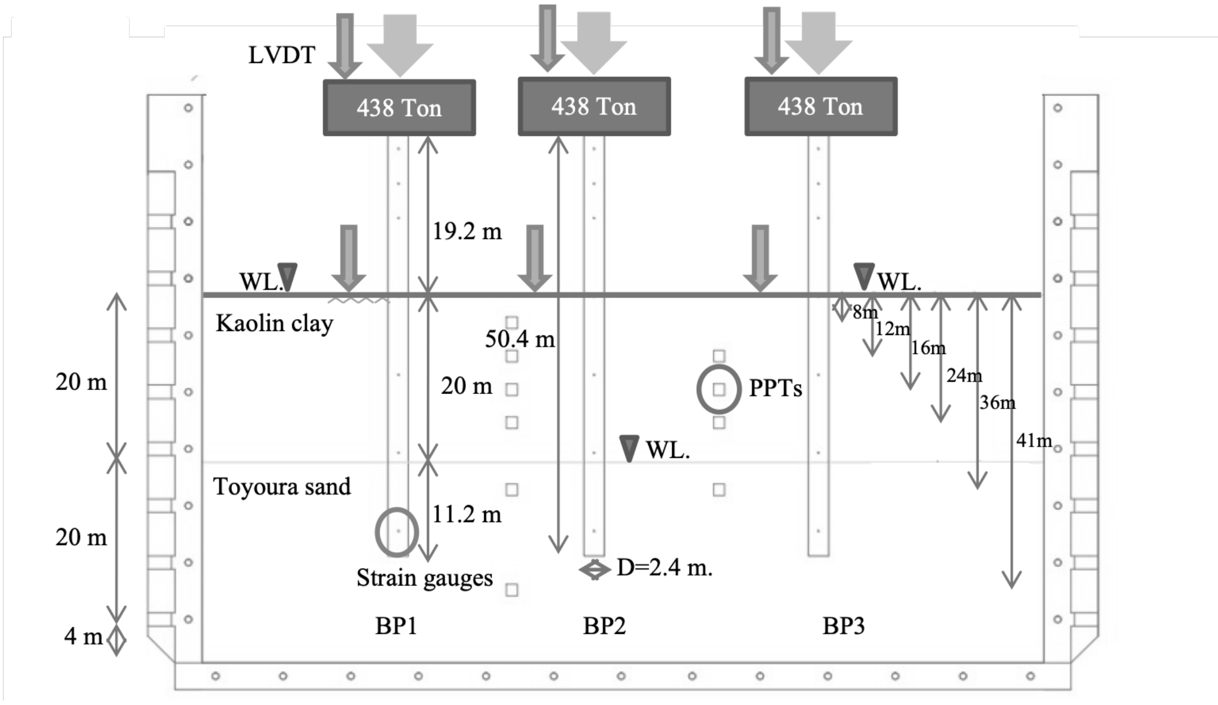

Fig.4 Testing procedure of centrifuge tests

2.1.6 Instruments

The focus of the sts is the results of the pile bearing capacity. Three types of instruments were installed in the soil model. Firstly, linearly variable differential transformers (LVDTs) were installed at the pile caps and the ground surface to measure the surface soil displacements. Secondly, pore water pressure transducers (PPTs) were installed in both soil layers. Thirdly, strain gauges were installed inside the model pile. After all centrifuge tests had been performed, the undrained shear strength of the soil was measured by pocket vane shear tests. Additionally, cameras were installed around the strongbox to monitor the external movement and groundwater level in the model during the testing.

2.1.4 Testing procedures

This study uses a 2D model box. The model had dimensions of 350x750x1245 mm. A water system was installed at the bottom of the model box with two holes to control the groundwater level and distribute the water. Then, the two soil layers were prepared. Toyoura sand was released from a rate hopper and spread to a fixed height to control the density of the sand (1.53 t/m^3). The sand was filled in, layer by layer, with a maximum thickness of 50 mm per layer, until reaching a total thickness of 300 mm. After that, the groundwater level was increased by the standpipe system to saturate the sand for about 24 hours. Then, water was released from the model box by the standpipe system to make the uniform density of the sand layer. Next, the Kaolin clay was compacted on top of the sand layer by a density control method to a thickness of 250 mm. Then, the soil model was drilled to install the three-pile model, as shown in Fig.4. The piles were installed in both the stiff clay layer and the medium-dense sand layer. The pile tips were driven into the medium dense sand layer about 140 mm from the interface of the sand layer. After installing all the instruments in the model box, a balance weight was equipped on the opposite side of the model box to balance the centrifuge machine during testing. A summary of the centrifuge test is given in Table 4 and Fig.5. The testing model consisted of the model box and one water tank to control the water level.

The centrifuge test consisted of three stages that were carried out at an acceleration equal to 80 times the force of gravity (80 g). Each stage is related to the groundwater level at a different period. The three stages are called BP1, BP2, and BP3. The first stage, BP1, refers to the stage in which the bearing capacity behavior of the soil around a single pile is investigated by performing a pile load test after the groundwater level reaches the ground surface. This stage represents the original groundwater in the past before the occurrence of the pumping issue. The second stage, BP2, refers to the stage in which the groundwater level decreases to the interface of the sand layer and clay layer after which a pile load test is performed. This stage represents the decrease in groundwater due to the high pumping rate during the period of increasing industrial development. The third stage, BP3, is similar to the BP1 stage. The groundwater level reaches the ground surface again after the BP2 stage and a pile load test is performed on the pile head. Every test was performed at an acceleration of 80 g with the pile load test rate of 2 mm/min by ASTM, as in [11].

Table 4 Summary of centrifuge test

Testing No.	The water level in prototype (m)	The water level in the model (mm)	Initial water content (%)
BP1	0	0	27
BP2	20	250	27
BP3	0	0	27

Note: BP refers to the type of pile, namely, a bored pile, and the number after BP is the number of single piles.

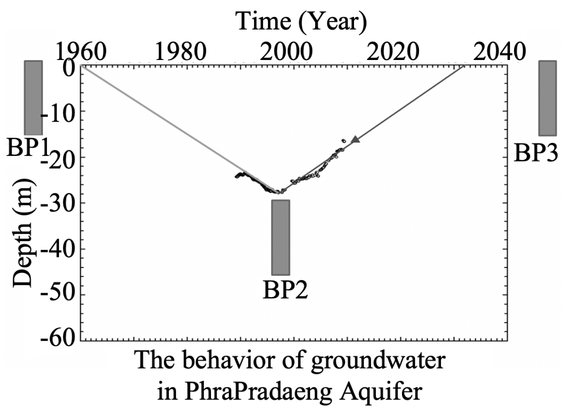

Fig.5 Stage of centrifuge test

4. RESULTS AND DISCUSSION

The results of the pile load tests in the centrifuge test will be detailed here. The results of the three stages were separated into three parts. The first set of results shows the settlement of the pile and the ground surface during the pile load tests. The second set of results shows the bearing capacity and the unit skin friction during the pile load tests. The last set of results shows the undrained shear strength values after testing at 0 g.

4.1 Settlement

Based on Figs. 6 to 8, the settlement behavior between a single pile and the ground surface in each stage condition of the groundwater level during the pile load tests is given. The circular marker in each test, representing the settlement of the ground surface, shows that a small settlement occurred in all the tests compared with pile settlement. On the other hand, the triangular marker shows that a very large settlement occurred in the first pile load test due to the soil model just starting to consolidate and the voids between the soil particles filling with water due to groundwater level reaching the ground surface. In the same way, it was found that the second test had the smallest settlement because of the decrease in water level to the soil interface between the clay and the sand as the clay layer was consolidated. The last test showed that more settlements occurred than in the second test, but still less than in the first test. These results confirm that the groundwater level directly affects the settlement behavior of the soil around the piles in every stage.

4.2 Bearing capacity

The pile load capacity is discussed in this section. The strain gauge results represent the strength of the soil around the piles. Based on Fig. 9, the pile load is directly affected by the changing water level. The first stage has the smallest load capacity due to the high groundwater level and the short-term consolidation. After consolidation, the bearing capacity is significantly increased. Especially in the last stage, BP3, the condition is represented whereby the groundwater level rises and the Kaolin clay layer has already consolidated for the longest period. Fig. 10 confirms that the period of consolidation has a huge effect on the strength of the soil around a single pile. However, the unit skin friction results for the sand layer are not related to the consolidation condition in each test. The third stage has a lower unit skin friction value than the second stage because the groundwater rises to the ground surface leading to high pore-water pressure. The soil strength of each test is explained in terms of the effective stress in Fig. 11. The effective stress is equal to the total stress minus the pore water pressure. The groundwater level at each stage refers to the pore water pressure that directly affects the effective stress. Thus, the second test has the highest effective stress due to the decrease in water to the interface of the soil.

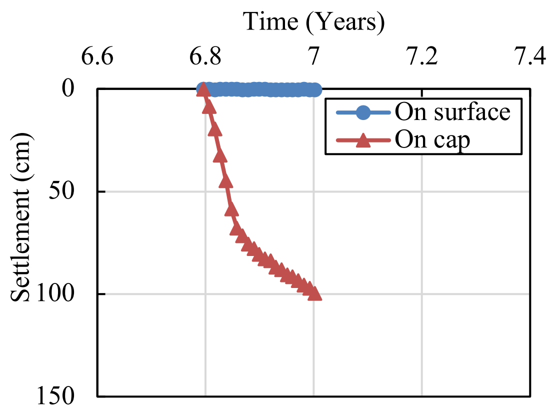

Fig.6 Settlement during the first pile load test

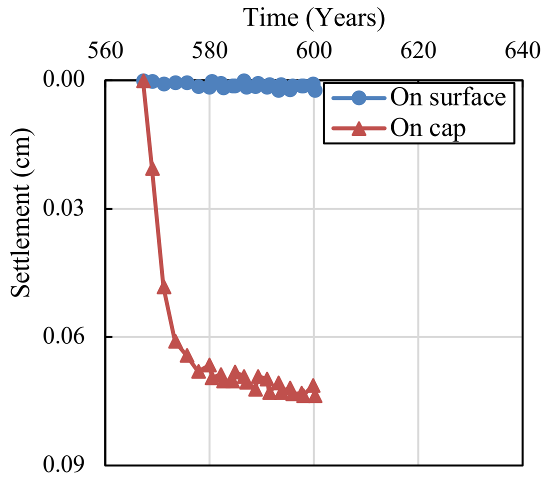

Fig.7 Settlement during the second pile load test

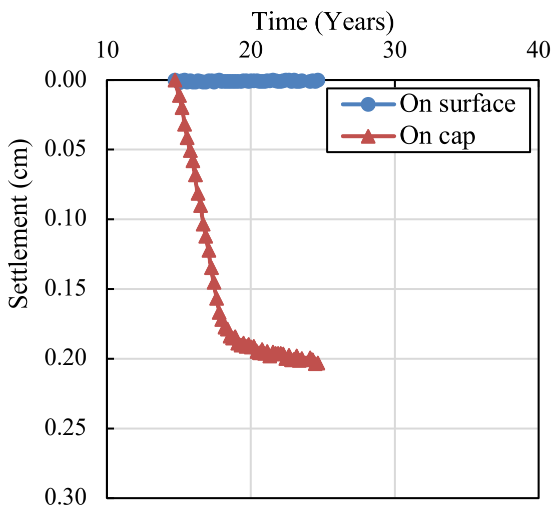

Fig.8 Settlement during the third pile load test

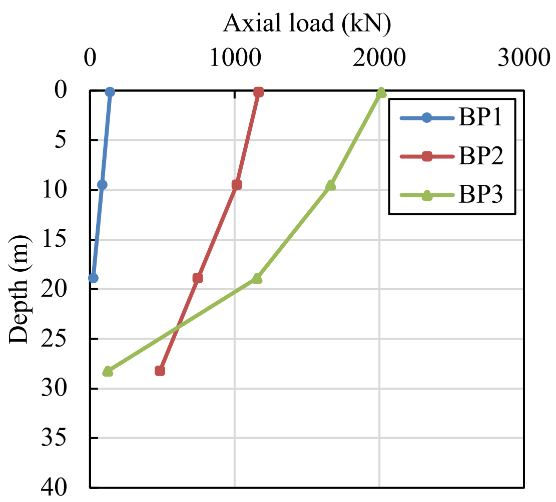

Fig.9 Comparison of an axial load of each test

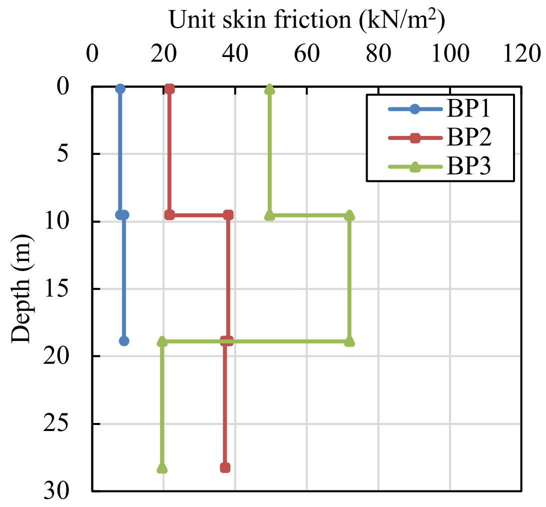

Fig.10 Unit skin friction of each test

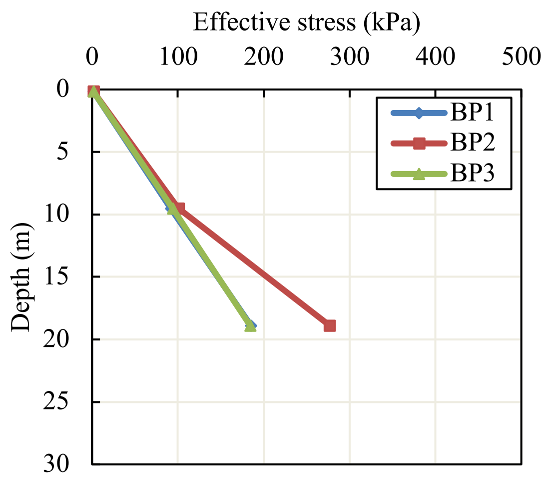

Fig.11 Effective stress of each test

4.3 Soil strength

The undrained shear strength, after the centrifuge tests were done at 0 g, is discussed here. Fig. 12 shows a comparison of the undrained shear strength between the centrifuge test results and the results obtained by other researchers. The results revealed that many researchers obtained almost the same undrained shear strength values at every depth [12]–[15]. Even the results of the pocket vane shear tests showed higher strength than in the tests done by others researchers, but still with the same trend. Additionally, the authors confirm the values when using the Modified Cam-Clay theory to recheck the values of the pocket vane shear tests, as seen in Fig. 13. The results reveal that the values of the undrained shear strength from the vane shear tests are lower than those of the Modified Cam-Clay theory at each soil depth.

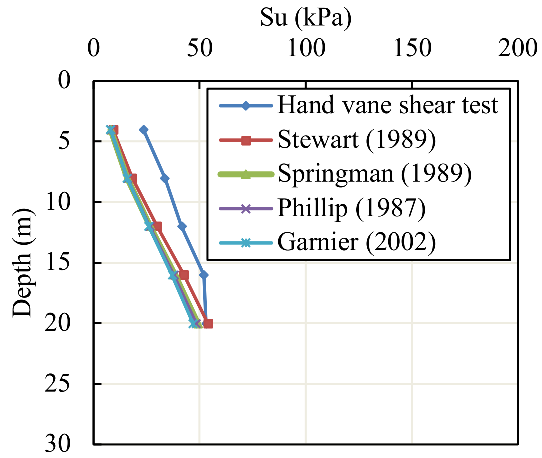

Fig.12 Comparison of undrained shear strength

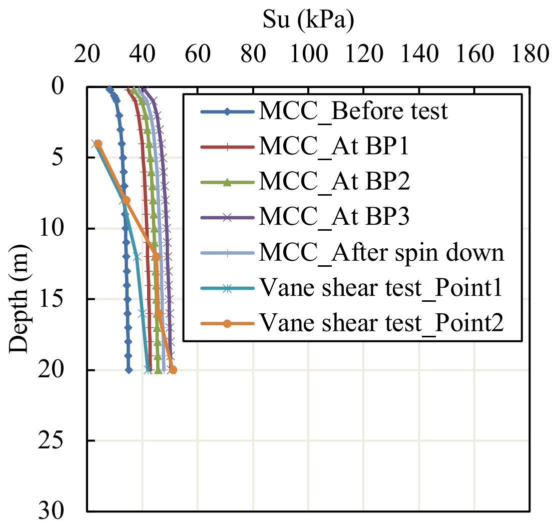

Fig.13 Comparison of undrained shear strength

5. CONCLUSION

This paper focused on a comparison of the behavior of a single pile during changing groundwater levels by considering the soil strength parameters, ground settlement, and pile head settlement. All the results of this research were compared with those of a previous study. It was proven by hand calculation that the trends of the results are the same. For the axial load behavior of a single pile, the bearing capacity of the soil around the pile was found to be related to the water level and the consolidation of the soil. The bearing capacity of the clay layer increased because of an increase in the effective stress due to a decrease in the groundwater level. On the other hand, the bearing capacity in the last of the three stages was seen to increase because of the consolidation process in the clay layer when the groundwater rose again. However, the bearing capacity in the sand layer was found to depend on the groundwater level or the pore water pressure, as in the effective stress theory. Therefore, this research can be used to estimate and design the bearing capacity of soil with changing groundwater levels.

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