International Journal of GEOMATE, Aug.,2021, Vol.21, Issue 84, pp.34-40
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.84.j2132
Geotechnique, Construction Materials and Environment

APPLICATION OF CENTRIFUGE MODEL TESTS TO SETTLEMENT BEHAVIOR UNDER GROUNDWATER RECOVERY

*Sutasinee Intui [1], Suttisak Soralump [2], Shinya Inazumi [3] and Ken-ichi Shishido [4]

[1] Graduate School of Engineering and Science, Shibaura Institute of Technology, Japan;
[2] Faculty of Engineering, Kasetsart University, Thailand;
[3] College of Engineering, Shibaura Institute of Technology, Japan;
[4] Tomec Corporation, Japan

*Corresponding Author, Received: 10 March 2021, Revised: 24 April 2021, Accepted: 15 May 2021

ABSTRACT: Land subsidence has been seen to have an effect in many countries, especially countries with areas of very soft soil. Settlement is generally found in high economic and developed locations and often depends on the increasing demand of humans for water. Namely, increased water consumption due to groundwater pumping results in an increase in settlement. All of these causes affect the changes in groundwater level. The government of Thailand has created rules to control groundwater consumption in order to solve subsidence and others problems. Changes in the water level directly affect soil settlement. This paper studies the land subsidence behavior by means of soil profiles obtained from Bangkok and the central area of Thailand, which are very similar, as a prototype soil model. The settlement behavior is examined through centrifuge tests performed after the water level drawdown due to water pumping. The groundwater level increases due to controlled pumping. Finally, the settlement results of the centrifuge tests are compared with the land subsidence characteristics of the Bangkok area. This research focuses on the testing methodology and soil settlement behavior. The land subsidence of Bangkok clay occurs continuously, but the vertical settlement of Kaolin clay is seen to be different at each stage of testing.

Keywords: Bangkok clay, Centrifuge, Groundwater, Land subsidence, Settlement

1. INTRODUCTION

Many countries, including England, Mexico, Indonesia, USA, China, and Japan, have problems with soft soil, such as differential settlement, the slope failure of embankments, and groundwater leakage to underground structures during changes in the groundwater level. Pore water pressure and soil suction are the main two factors influencing the theory of consolidation. Changes in the groundwater level directly affect the soil settlement behavior. Thus, this study is focused on the displacement factors in Bangkok clay. The results of displacement during changes in the groundwater level are explained through the use of a centrifuge machine at the Hong Kong University of Science and Technology (HKUST). Then, a comparison is made between the settlement behavior of Kaolin clay (used instead of a stiff Bangkok clay) and Toyoura sand in centrifuge tests. This paper only explains certain parts of the testing and may not include all of the methodology. The other information was reported in a previous paper by the authors [1].

Many researchers have studied land subsidence behavior. Each of their tests has a different scope of study and methodology. Lui et al. studied land subsidence using borehole extensometer compaction measurements taken in the Houston-Galveston region of Texas [2]. Poland and Davis studied the relationship between the decline in water level and the rate of subsidence [3]. The causes of land subsidence are the drop in water level and the weight of the overlying live load. Most of the pressure head or pore water pressure in the Bangkok area has decreased due to the removal of groundwater. During the period of research, Paveenchana and Brand reported that the land subsidence in Bangkok occurs as the compression of the upper clay layer and should play a major role in the surface subsidence [4], [5]. The AIT (Asian Institute of Technology) and DMR (Department of Mineral Resources) found that the maximum rate of the total land subsidence reached 10 cm/year, with distributions of 40% and 60% to the upper and lower clay layers, respectively [6]. Many researchers have concluded that clay is the main cause of land subsidence. It should be noted that changes in the water level also affect the bearing capacity of piles. JICA implemented a groundwater model using MODFLOW and MOCDENSE MT3D software [7]. The results revealed that the land subsidence rate was 20 mm/year in central Bangkok and reached 50 mm/year in the vicinity of Bangkok. In the same way, changes in the groundwater level are significantly affected by the effective stress because the increase in effective stress in the confining aquifers is equal to the decrease in fluid

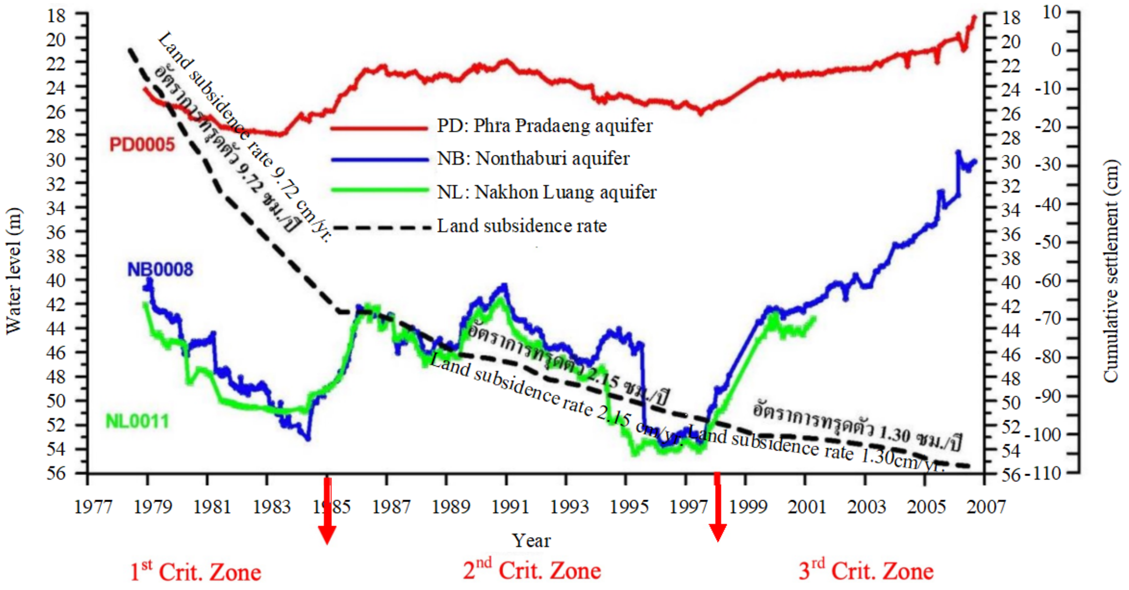

Fig. 1 Relationship between ground water level and settlement of Bangkok clay

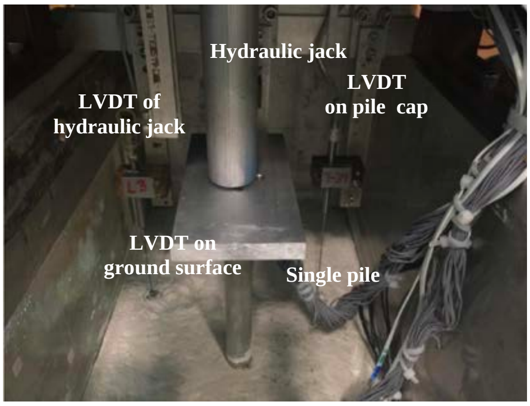

Fig. 2 Instrumentation used

pressure.

This research addresses the soil characteristics of the Bangkok area of Thailand. The soil profiles consist of clay layers alternated with sand layers until reaching the bedrock at a great depth. Each layer of sand has an aquifer for groundwater pumping. Research by the DGR (Department of Groundwater Resource) found that the groundwater, altering the local extraction rate, led to a rise in groundwater back toward that of the pre-1997 level [8]. Since 1997, the reduction in groundwater level has stopped at least 27 meters from the ground surface and the rate of decrease is approximately 1 to 3 cm/year due to the rules now governing the controlled usage of groundwater. This controlled groundwater pumping has led to a rate of increase in groundwater recovery of approximately 0.7 to 1 cm/year.

Changes in the groundwater level directly affect the land subsidence [8]. Figure 1 shows that ground settlement is related to changes in the groundwater level. The boreholes at Ramkhamheang University revealed that not only changes in the groundwater level, but also land subsidence, occurred continuously even during the groundwater level recovery period, but that the land subsidence rate was lower than the groundwater decrease period. Serious land subsidence of more than 10 cm/year occurs due to uncontrolled pumping because the aquifer and the overlying clay layer are under substantial stress [9]. Thus, land subsidence still occurs even when the groundwater in all the aquifers increases.

2. CENTRIFUGE MODEL TESTS

2.1 Apparatus

This study shows the land subsidence behavior during testing in three stages. The difference in the stages is the groundwater level. The first stage is when the water level is at the ground surface or the original stage, referring to the situation before the groundwater has decreased or before pumping has been performed. The second stage is when the water level decreases to the minimum level; it means groundwater has been pumped due to high consumption. The last stage represents the recovery of the water level to the ground surface or the original stage. This stage occurs after the pumping control law has been applied, when the groundwater level tends to increase to the ground surface. All three stages affect the soil settlement behavior. Therefore, this research will interpolate the displacement data from the centrifuge testing and make a comparison with the settlement results for Bangkok clay.

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	mm
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	mm
Liquid limit, LL	46±2	%
Plasticity limit, PL	19±2	%
Silt	23	%
Sand	43	%
Clay	34	%

2.1.1 Instruments

Focus here is placed on the settlement of the ground surface during the changes in groundwater level. As seen in Fig. 2, the following instruments were used to measure the pore pressure and surface soil displacement.

The pore water pressure was measured with PDCR-81 miniature pore water pressure transducers (PPTs). Each PPT was calibrated before its use by varying the pressure from -90 to 500 kPa and applying the power supply of DC 5V to monitor the pore pressure during testing. Eight PPTs were used in the clay layer and two PPTs were used in the sand layer. Additionally, one PPT controlled the water level in the water tank nearby the model box.

Measurement of the surface soil displacement was done with linearly variable differential transformers (LVDTs) of the Macro sensor's PR 750 series. These LVDTs have two different strokes of ±20 mm and ±80 mm and use an output voltage of ±10 V under the power supply of DC 10 V. The LVDTs were calibrated by the relationship between the displacement and the output voltage. At each stage of the water level, two LVDTs were installed on the ground surface.

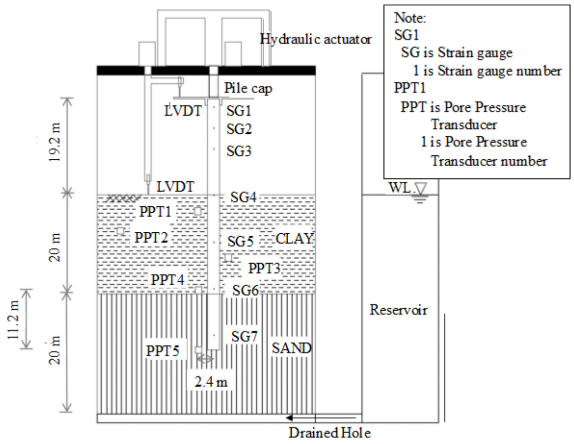

Fig. 3 Side view of the model

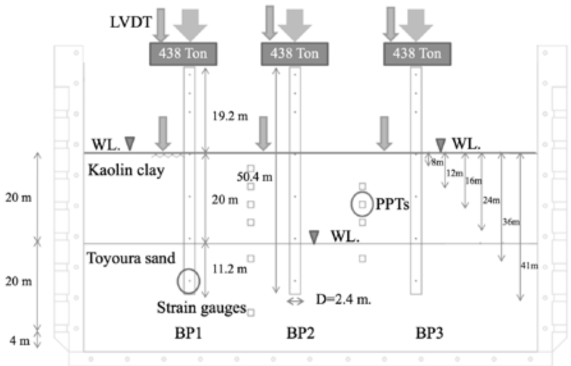

Fig. 4 Front view of the model

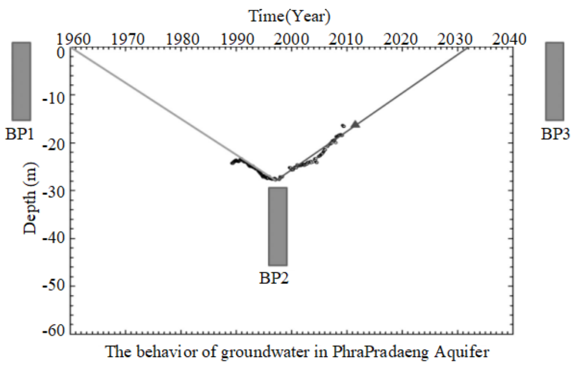

Fig. 5 Groundwater level variation of the model test

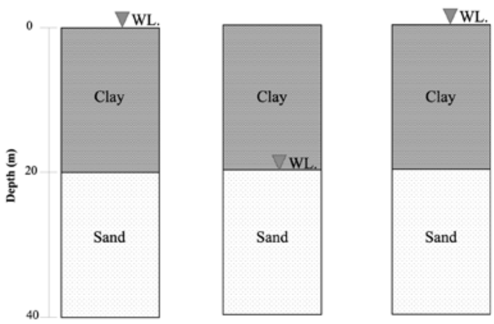

Fig. 6 Water level comparison of each test

2.1.2 Soil model

The model considers the high percentage of load transfer from a single pile in the Bangkok area of Thailand. The two soil layers are chosen as stiff clay and dense sand. Thus, the soil model for the centrifuge tests consists of two layers, namely, the lower layer of Toyoura sand which is the dense sand, and the upper layer of compacted Kaolin clay which is the stiff clay. The base properties of Toyoura sand are shown in Table 1, the properties of Speswhite Kaolin clay are shown in Table 2 [10], and the properties of stiff Bangkok clay are given in Table 3 [11].

2.1.3 Water flow system

Changes in the water level are controlled by the drain line under the soil model. The water flow line reflects the occurrence of the groundwater drawdown and the groundwater recovery. Two drainage holes were made in the corner box. Each pipe was covered by geotextile to protect the waterspout and to prevent the holes in the pipe from being filled with sand.

2.2 Procedures

In the present study, a 2D model box with the dimensions of 350 mm × 750 mm × 1245 mm was used. A waterspout line was equipped after cleaning the model box. Pluvial sand was poured into the strong box through a hopper every 10 mm of each sand layer until a thickness of 250 mm according to the required density of Toyoura sand of around 1.55 t/m^3. Then, the water level was increased to saturate the Toyoura sand over the course of one night. Afterwards, the water was released from the model box through the waterspout line. At the sand saturation stage, compact clay was placed on top of the sand by mixing Speswhite Kaolin powder with water (27% water content) by compaction until the thickness of 250 mm. The target density was 1.65 t/m^3 and the undrained shear strength was 35 kPa. Next, holes were excavated by the dry process method in order to install three single piles. Then, the instruments were installed into the model, as seen in Figs. 3 and 4. Strain gauges were installed inside the segment piles to prevent water from entering the model, along with the PPTs, LVDTs, and hydraulic actuator. All the instruments were linked to the data logger so the data could be read while the model was spinning.

The centrifuge tests were divided into three steps related to the water level, as seen in Figs. 5 and 6. The tests were run from 0 g to 80 g and then water was released to the water level at the surface. After the water level had stabilized, a pile load test was conducted at BP1 (BP means bored pile and 1 is the number of piles) until the pile capacity was constant. Then the model was spun down to 0 g in order to move the hydraulic actuator to the next pile. The model was spun up to 80 g again, the water level decreased to the interface of soil until the water level became constant, and a pile load test was then performed on BP2. After spinning down BP2, the hydraulic actuator was moved to BP3 for testing like the first test.

3. ANALYSIS OF SETTLEMENT

The model focuses on soil settlement, and the testing is verified by the changes in pore water pressure in the clay and sand layers. The main results are interpolated and show the settlement of the saturated soil and the unsaturated soil.

The saturated soil shows that water filled up the voids [12]. Terzaghi formulated the principle of effective stress that can be expressed in the form of two propositions. The first is that all the measurable effects of the changes in stress, soil distortion, and changes in shearing resistance, depend on the effective stress. The second point is that the effective stress is defined as the excess total stress applied over the pore pressure [13], [14]. Terzaghi's equation can be used for the effective stress of the soil, as follows:

$$\sigma' = \sigma - u \tag{1}$$

The unsaturated soil condition means that some of the water in the voids of the soil has dissipated and been replaced with air, so the soil here is partly unsaturated and partly saturated. Many attempts have been made to extend the principle of effective stress. Unsaturated soil has soil moisture suction or pressure deficiency in the soil water which contributes directly (p") to the effective stress in the soil. The equation for that is

$$\sigma' = \sigma + p'' \tag{2}$$

4. RESULTS AND DISCUSSIONS

Among the results of the centrifuge tests, only the displacement behavior of each stage is considered. In Figs. 7 to 9, the pore water pressure is seen to develop from Stage 1 to Stage 3. The results at each stage show that the water level is changing.

Following the changes in the water level in the Bangkok area, the groundwater level had stayed on the ground surface before the groundwater pumping. The first stage refers to the water level developing through each soil layer to the ground surface, as shown in Fig. 7. The figure shows the pore pressure characteristic that the changes in water level are related to the pore water pressure developing and continuing until the hydrostatic condition in both the Kaolin clay and Toyoura sand. In part of the

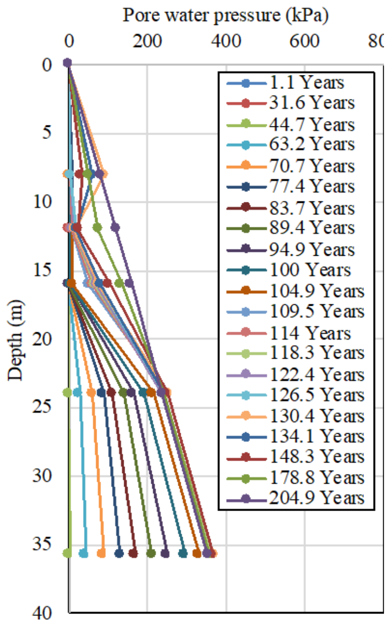

Fig. 7 Pore water pressure at ground surface before decrease in water level

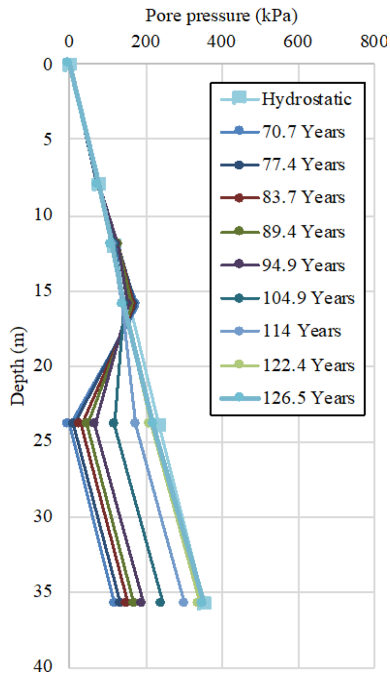

Fig. 9 Water level at ground surface

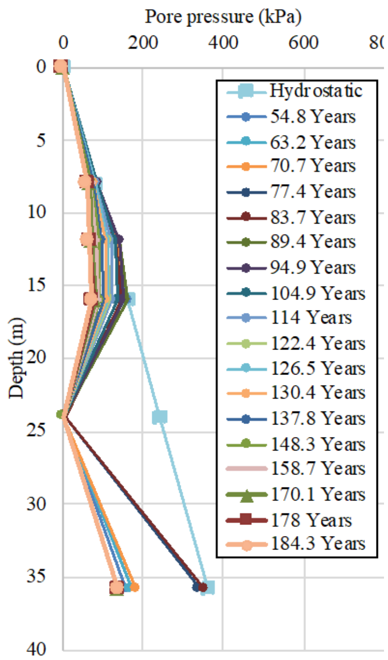

Fig. 8 Pore water pressure at minimum level

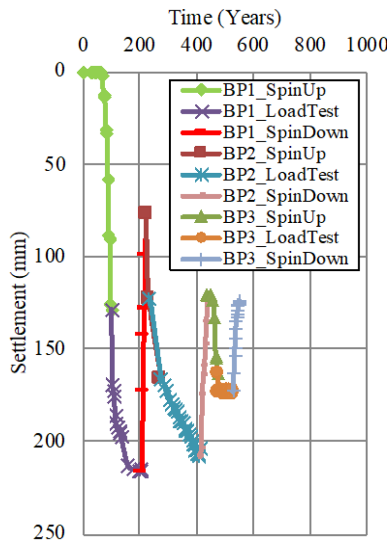

Fig. 10 Settlement development on ground surface

clay layer, it was found that the pore water pressure of Kaolin clay tends to move very slowly to the hydrostatic condition compared with the Toyoura sand. This behavior is proof that the soil particles affect the flow rate of water. Toyoura sand has larger voids between the soil particles and higher permeability than Kaolin clay. Thus, the flow rate of the pore water pressure in the Toyoura sand layer is faster than that in the Kaolin clay layer.

The second stage, seen in Fig. 8, refers to the continuous pumping of groundwater resulting from rapid industry development. It is affected by the water drawdown that occurred in the past. Normally, the clay layer is impervious. The voids between the clay particles are filled with water or air. The unsaturated condition occurs during the water drawdown in the clay layer.

The last stage, seen in Fig. 9, is when the water level has recovered to the ground surface. This behavior is similar to that of the first stage because the groundwater tries to reach to ground surface. However, the difference is that there are fewer voids in the clay in the last stage than in the first stage.

Fig. 9 shows that the water level recovery takes more time than in the first stage.

However, the voids changing between the interfaces in the clay layer show that the quantity of voids directly affects the amount of soil displacement. Additionally, the pore water pressure affects the displacement too. It is seen in Fig. 10 that soil settlement continuously occurs in each stage, and that soil settlement still occurs with the drawing down and rising up of the groundwater level.

The settlement behavior was compared between the centrifuge test and the previous study of the Bangkok area. The soil displacement is considered through the relationship between the effective stress and the settlement. In terms of the effective stress equation for the unsaturated soil, the effective stress increases while the settlement increases. The settlement of Kaolin clay is similar to that of Bangkok clay. It is related to the term principle of effective stress equation for unsaturated soil, even though the two types of clay have similar basic properties. The saturated and unsaturated conditions affect the consolidation state. The properties of Bangkok clay have more plastic than Kaolin. All of these data prove that Bangkok clay and Kaolin clay have almost the same trends in settlement.

5. CONCLUSIONS

The displacement results for three periods were analyzed by a centrifuge machine, and the verified results showed that the settlement value and the behavior between the tested Kaolin clay and Bangkok clay were close to each other. Due to the use of Kaolin clay in this testing, the properties of the two soils had some parameters that differed, such as the water content, liquid limit (LL), plasticity limit (PL), and plasticity index (PI). As Kaolin clay has a lower liquid limit compared with Bangkok clay, its effect on the settlement value changes due to the groundwater level. Normally, land subsidence occurs continuously in Bangkok clay along with groundwater level drawdown and recovery. In the same way, the settlement also occurs continuously in Kaolin clay. The settlement rate of the groundwater drawdown is significantly higher than the recovery period. In conclusion, the land subsidence behavior depends on the changes in the groundwater level. This ensures that along with groundwater recovery, settlement still occurs continuously even when the settlement rate is lower than the drawdown period. However, this research has expressed the limitations of using Kaolin clay as a model soil in any physical model testing. Thus, researchers must consider the basic properties of the model soil especially in the settlement model.

6. ACKNOWLEDGMENTS

The author would like to thank the Geotechnical Research and Development Center (GERD) for supporting every aspect of this research. Gratitude is also extended to the Hong Kong University Science and Technology (HKUST) for providing the necessary machines and other equipment for such testing. Finally, we would like to thank every researcher and technician at HKUST and GERD for their help during the testing and the analysis of the data.

7. REFERENCES

[1] Intui S. and Soralump S., The Vertical Bearing Capacity Behavior of Single Pile by Geotechnical Centrifuge, Kasetsart Engineering Journal, Vol. 31, No. 104, 2018, pp. 55-68.

[2] Lui Y., Li J. and Fang Z. N., Groundwater level change management on control of land subsidence supported by borehole extensometer compaction measurements in the Houston-Galveston Region, Texas, Geosciences, Vol. 5, Issue 9, 2019, pp. 1-9.

[3] Poland J. F. and Davis G. H., Subsidence of the land surface in Tulare-Wasco (Delano) and Los Banos-Kettleman City area, San Joaquin Valley California, U.S. Geological Survey Professional Paper: Land Subsidence in the San Joaquin Valley, California, As of 1972, 1956, Vol. 37, No. 3, pp. 287-296.

[4] Paveenchana, T., The Effect of Deep Well Pumping on Land Subsidence in the Bangkok Area: M. Eng. Thesis, Asian Institute of Technology, Pathumthani, 1970.

[5] Brand, E.W. and Paveenchana, T., Deep-Well Pumping and Subsidence in the Bangkok Area, Forth Asian Regional Conference Proceeding, Soil Mechanics Foundation Engineering, Bangkok, 1971, Vol. 1, pp. 1-7.

[6] Asain Institute of Technology (AIT) and Department of Mineral Resources (DMR), Groundwater Resource in Bangkok Area: Area Development and Management Study, Comprehensive Report 1978-1982, 1982.

[7] Japan International Cooperation Agency (JICA), The study on management of groundwater and land subsidence in the Bangkok metropolitan area and its vicinity, 1995.

[8] Department of Groundwater Resource (DGR), Groundwater situation in Bangkok and urban area, 2012.

[9] Buapeng S. and Wattayakorn G., Groundwater situation in Bangkok and its Vicinity,

Proceedings of RIHN International Symposium on Human Impacts on Urban Subsurface Environments, 2005, pp. 60-63.
[10] Horpibulsuk S., Yangsukkasaem N., Chinkulkijiniwat A. and Yan J.D., Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. Applied Clay Science, 2011, pp. 150-159.
[11] Surasak C., Likitlersuang S., Wanatowski D., Balasubramaniam A., Erwin O. and Guan H., 2012, Stiffness and strength parameters for hardening soil model of soft and stiff Bangkok clays, Soil and Foundations, Vol. 52, No. 4, pp. 682-697.
[12] Jennings, J. E. B. and Burland, J. B., Limitations to the use effective stresses in partly saturated soils, Geotechnique, Vol. 12, Issue 2, 1962, pp. 125-144.
[13] Terzaghi, K., A method of calculating the efficient of permeability of clay from the variation of hydrodynamic stress with time, Vol. 132, 1923, pp. 125-138.
[14] Terzaghi, K., Bearing capacity of shallow foundations, International Association for Bridge and Structural Engineering, 1932, pp. 659-672.