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Effect of Ground Subsidence on Load Sharing and Settlement of Raft and Piled Raft Foundations

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Abstract**—**In this paper, two centrifugal model tests (case 1: raft foundation, case 2: 2x2 piled raft foundation) were conducted in order to evaluate the effect of ground subsidence on load sharing among piles and raft and settlement of raft and piled raft foundations. For each case, two conditions consisting of undrained (without groundwater pumping) and drained (with groundwater pumping) conditions were considered. Vertical loads were applied to the models after the foundations were completely consolidated by selfweight at 50g. The results show that load sharing by the piles in piled raft foundation (piled load share) for drained condition decreases faster than that for undrained condition. Settlement of both raft and piled raft foundations for drained condition increases more quickly than that for undrained condition. In addition, the settlement of raft foundation increases more largely than the settlement of piled raft foundation for drained condition.

Keywords**—**Ground subsidence, Piled raft, Load sharing, Centrifugal model test.

I. Introduction

DUE to the increase in pumping of groundwater, ground subsidence has occurred in some large cities such as Ho Chi Minh, Bangkok, Mexico City and Shanghai City. Effects of land subsidence from deep well pumping on differential settlement of many buildings in Bangkok area are shown in [1]. The use of compensated friction pile foundation to reduce settlement of buildings on the highly compressible volcanic clay of Mexico City was described by [2]. A comparison of ground water pumping rate and ground surface subsidence rate of Shanghai City and some results of ground subsidence observed in Ho Chi Minh area were presented in [3].

Most of moderate and high-rise buildings, nowadays, are supported by raft and piled raft foundations. Reference [4] shows examples of the use of piled raft with piles as settlement reducers in different types of soils.

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In this regard, piled load share is the most important factor to estimate the settlement of the foundations. Several researched works [5], [6], [7] have presented and given explanations on this relationship. However, few works focused on foundations under the effects of ground surface subsidence.

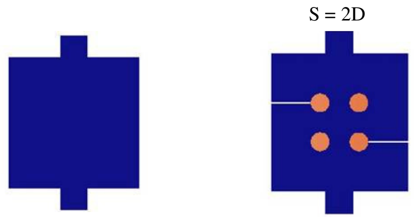
This study aims to draw out the effect of ground subsidence on load sharing between raft and piles which influences the settlement of the piled raft foundations.

The models of raft and piled raft foundations on soft clay were divided in two cases and were conducted by centrifugal testing. The results of two tests were presented and the effect of ground subsidence was discussed.

II. Centrifugal Modeling

A. Testing Cases

In order to evaluate the effectiveness of piles and to estimate the effects of ground subsidence causing by groundwater pumping on raft and piled raft foundations, two cases were conducted in this study. Case 1 is for a plain raft foundation and case 2 is for a 2x2 piled raft foundation, as shown in Fig.1. Two ground water conditions including undrained (without groundwater pumping) and drained (with groundwater pumping) were considered in centrifugal tests.



(a) Case 1: plain raft (b) Case 2: piled raft

Fig. 1 Two cases were conducted in centrifuge tests

B. Testing Apparatus

The centrifugal testing equipment of the Disaster Prevention Research Institute (DPRI) in Kyoto University was used for this study [8]. Total allowable weight is 140 kg. The effective radius of the centrifuge is 2.5 m and the maximum payload is 24 G-ton. Fig.2 shows a photo of testing apparatus used in this study. The soil chamber had the inside dimension of 240 mm x 240 mm x 335 mm, and the thickness of 30 mm. The acceleration applied to the testing models was 50g. The models were scaled down to ratio of 1/50. Scaling laws

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presented in TABLE I were applied for the relationship between the model and the prototype.

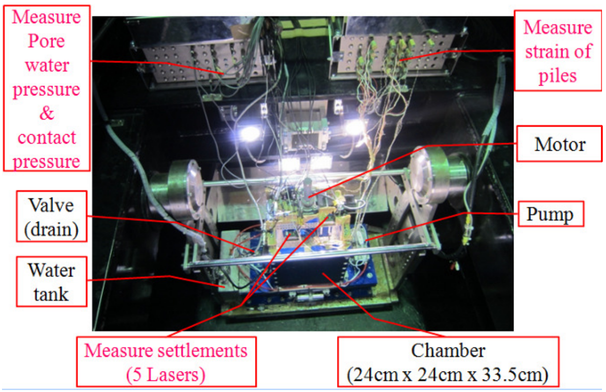


Fig. 2 Photo of testing apparatus used in this study

TABLE I
SCALING LAWS

Parameters	Scale*	Parameters	Scale*
Acceleration	N	Density	1
Length	$1/N$	Mass	$1/N^3$
Stress	1	Force	$1/N^2$
Strain	1	Time (diffusion)	$1/N^2$
Stiffness	$1/N$	Strain rate	N^2

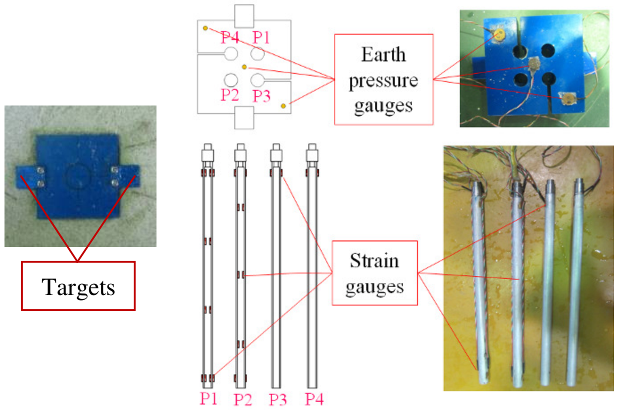
*Scale: model/prototype. *N*: scale factor

C. Foundation Models

Raft and piled raft models are shown in Fig.3. The raft model was made of aluminum alloy and was designed to be a stiff raft. The size of the raft for both cases was 56 mm long, 56 mm wide and 15 mm thick. The dimension of the raft was chosen to satisfy the allowable weight, to minimize boundary effects of the chamber wall, and also to reduce the consolidation time. The ratio between the edge of chamber and the equivalent edge of raft was about 4.3 beyond the effect of rigid wall which was estimated to be at 3-4 [9]. The model pile was made of closed-end aluminum pipe, which had an outside diameter of 8 mm and the thickness of 1 mm. The length of the pile was 200 mm, taken with the slenderness ratio of 25. The pile diameter was chosen to ease the attachment of strain gauges on its surface. Young's modulus of piles was about 68 GPa and Poisson ratio was taken as 0.34 while the unit weight was about 2.7 g/cm3.

D. Instrumentations

Fig.3 and Fig.4 show the details of the instrumentation on the foundation and in the ground. Three earth pressure gauges were placed under the raft to measure contact pressure. Strain gauges were attached along pile shaft to measure axial load distribution. A motor was set on the top of the chamber to apply vertical load for foundations via a con rod (Fig.4). A load cell was attached at the tip of the con rod to measure applied load. Five laser transducers were used for the test. Two laser transducers were installed to measure the settlement of foundations while other two laser transducers were used to measure of ground surface settlement. The final laser transducer was used to record settlement at the middle of the ground via a telltale. Eight pore pressure transducers were buried in the ground to measure the change of water pressure during loading process. Six of them were embedded below the pile tip and other two were installed at the middle of pile shaft.



a) Raft b) Piled raft

Fig. 3 Instrumentations of foundation models

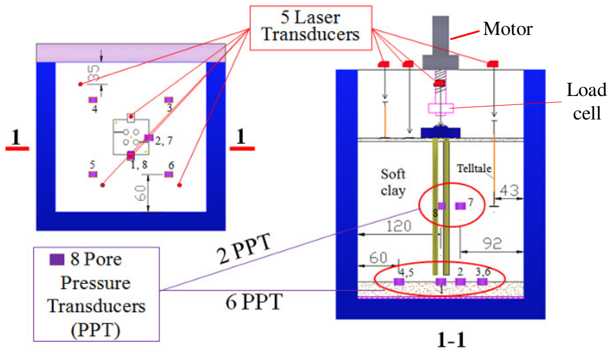


Fig. 4 Instrumentations of ground model

E. Soil Preparation

Method of soil preparation is shown in Fig.5. Three layers of soil including bottom sand, Kaolin clay and top sand were used in the chamber. Bottom sand was silica sand (grade 6) which was pluviated on the bottom of chamber till it got the thickness of 22mm. This layer was considered as stiff layer (D_r ≈ 80 ÷ 85). Kaolin clay was prepared in 2 layers with the total thickness of 205 mm. Lower layer of clay was preconsolidated at 50g with drained condition for 2 hours. Then upper layer of clay was poured on the lower layer and preconsolidated at 1g with drained condition for 12 hours before preconsolidating at 50g with undrained condition for 8.5 hours. Top sand was a 5 mm thickness of silica sand (grade 6). The effectiveness of this layer was to prevent the clay surface from softening to a slurry condition during the centrifuge tests and to facilitate the contact between the raft and the pile heads. It was poured on the surface of upper layer of clay after installing the testing piles which had been done at the end of preconsolidation.

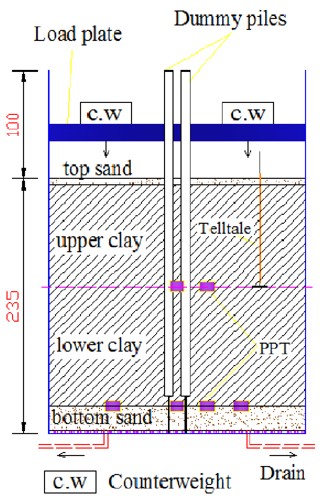
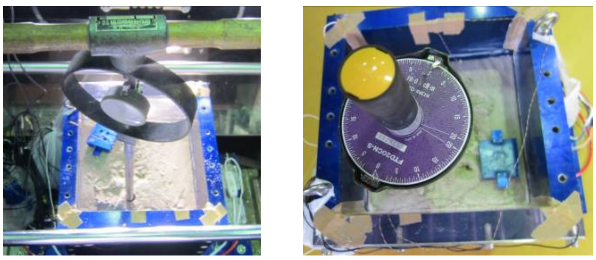


Fig. 5 Method of soil preparation

No scale effect was remarked for using top sand layer in the tests [10]. Grease was used to reduce friction of chamber walls. It is noticed that dummy piles were set into the chamber before preparing of bottom sand layer in case of test with piled raft foundation.

F. Soil Properties

Fig.6 shows a cone penetration test (CPT) and a vane shear test which were used for evaluating undrained shear strength S_u of soil. CTP and vane shear test were immediately performed after completing each centrifugal test. Diameter of the cone was 20 mm and it was penetrated into the soil at a rate of 10 mm/s. Capacity of vane shear tester (FTD20CN-S) was limited to 20 kPa and a vane factor of 0.8 was used for calculating vane shear test result. Fig.7 shows the result of undrained shear strength S_u of soil models.



a) CPT (b) Vane shear test

Fig. 6 Evaluation of shear strength of soil models

Tests for physical properties and consolidation test were conducted to determine properties of kaolin clay. Soil samples used for these tests were taken from the chamber after finishing preconsolidation. The result of consolidation test of kaolin clay is shown in Fig.8. TABLE II summarizes the properties of kaolin clay.

Properties of silica sand were determined from specific gravity test and sieve test. The specific gravity G_s of silica sand was 2.65. Fig.9 shows the result of sieve test of silica sand. Average particle size d_{50} of 0.22 mm and coefficient ununiformity C_u of 1.67 were deduced from Fig.9.

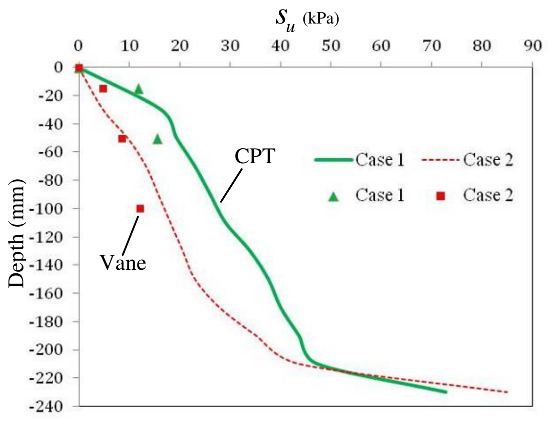


Fig.7 Shear strength of soil models

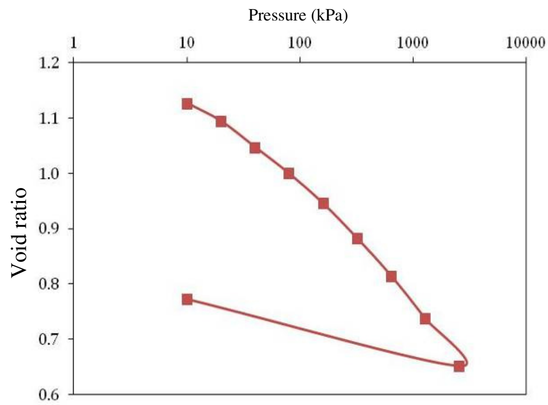


Fig. 8 *e*-logP curve of clay

TABLE II
PROPERTIES OF KAOLIN CLAY

Description	unit	Soft clay
Liquid limit: LL	%	45.54
Plastic limit: PL	%	33.72
Plasticity Index: PI	%	11.82
Water content	%	43.43
Specific gravity: G_s	-	2.634
Density: γ	$kN.m^{-3}$	17.18
Compression index: λ	-	0.133
Swelling index: κ	-	0.050
Void ratio (P = 37.7 kPa): e	-	1.052

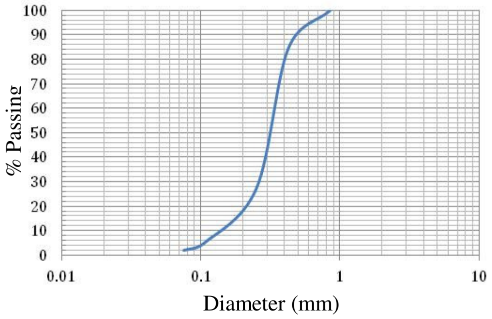
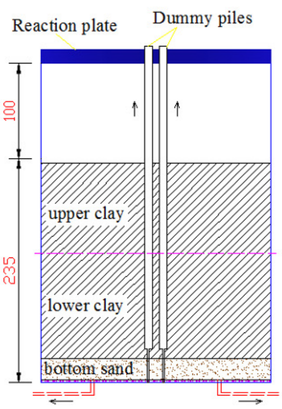


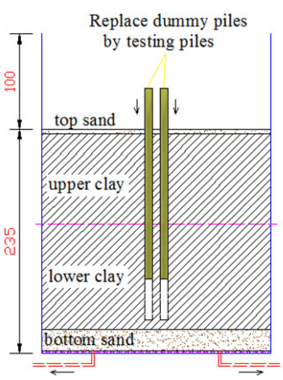
Fig. 9 Sieve analysis result of silica sand

G.Foundation Installation

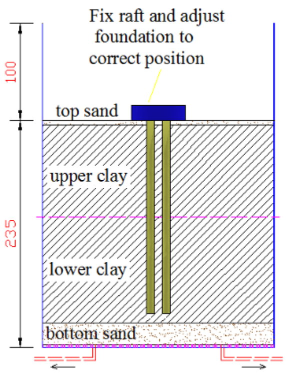
Fig.10 shows the method used for installing piled raft model. The piles was installed one by one on the soil (at 1g) at the end of the preconsolidation, after removing dummy piles with external diameter of 8 mm. Piled heads were carefully aligned to avoid inclined piles, different spacing and different embedded length as well. The raft was adjusted to ensure that its surface was horizontal by using water level.



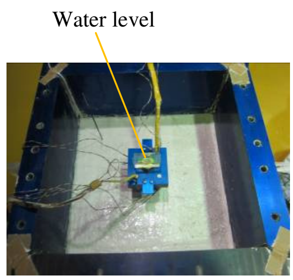
(a) Set up dummy piles



(b) Install testing piles



(c) Fix raft with pile head



(d) Check raft surface by water level

Fig. 10 Installation of piled raft model

As discussed in [10], the piles should be installed in-flight for an accurate simulation of prototype behavior (at 50g). The following stress increase due to self-weight could overcome the initial increase in horizontal stress around piles due to installation if the piles were installed at lower accelerations. This could lead to remarkable reduction in pile capacity. However, the results of current study were focused on the comparison of undrained and drained conditions for raft and piled raft foundations. Effects of methods of piled installation can be neglected.

H.Loading Stages

Because of low capacity of raft foundation, value of load used in case 1 was taken about 33 % value of load used in case 2. Loading stages including a prepared stage and two main stages are shown in Fig.11 and Fig.12.

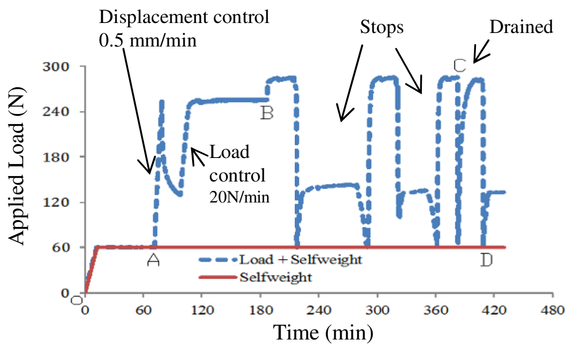


Fig. 11 Development of applied load with time in case 1

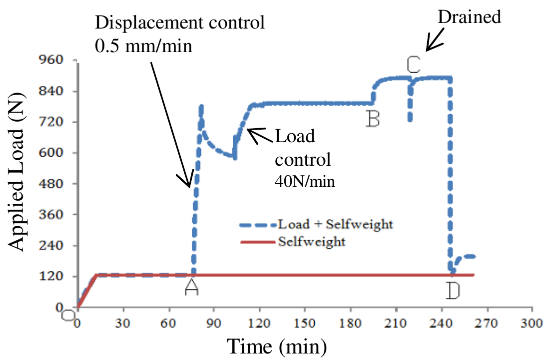


Fig. 12 Development of applied load with time in case 2

Prepared stage (OA): Both case 1 and case 2 were consolidated under selfweight of the foundations before applying vertical load.

Stage 1(AB): The loads were firstly applied to the foundations up to designed values (200 N for case 1 and 660 N for case 2) by displacement control (0.5mm/min) and waited for the dissipation of excess pore water pressure. During that process, the applied loads were decreased because of settlement of soil. Then the loads were increase to the designed values by loading control (20N/min for case 1 and 40N/min for case 2) and waited till the settlements of foundations were almost completed.

Stage 2(BCD): The loads were increased about 15 % current values in order to sure that the rafts were fully contacted with the soil surface. Then total loads were kept constantly till finishing the test. To simulate groundwater pumping condition, the soil was drained (point C) by a magnetic valve at the bottom of chamber. Unfortunately, two unexpected stops of centrifugal machine causing the remove of applied load occurred during this stage in case 1(see Fig.11).

III. Results and Discussions

A. Main results

Fig.13 shows settlements of raft foundation and ground surface with time in case 1. Raft foundation settled 4.5 mm and the ground surface settled 2.8 mm after prepared stage (OA). In stage 1 (AB), the settlement of the foundation increased remarkably because of applied load and it got the value of 13 mm at point B. However, ground surface showed a small settlement and it got a value of 3.5 mm at the end of stage 1. In stage 2, the settlement of foundation increased lightly when the applied load was increased 15 % current load of stage 1. The soil swelled largely when the centrifugal machine stopped (BC). At point C, the total settlement of foundation was 16.5 mm while the total settlement of ground surface was 5 mm. During drained condition (CD), the settlements of foundation and ground surface increased significantly. At the end of experiment (point D), the final settlement of foundation was 19.3 mm while a value of 10 mm was measured from the final settlement of ground surface. It is noted that the settlement of raft foundation increased about 2.8 mm and the settlement of ground surface increased about 5 mm in a period of 25 minutes of drained condition.

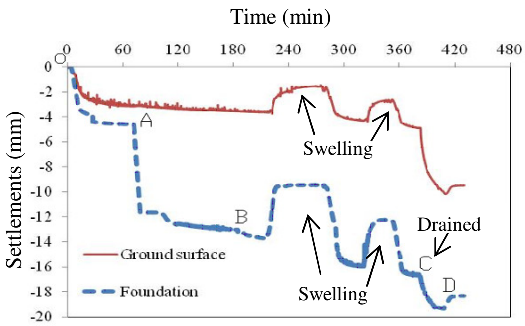


Fig. 13 Settlements of foundation and ground surface with time in case 1

Fig.14 presents settlements of piled raft foundation and ground surface with time in case 2. After prepared stage (OA), settlement of foundation was 0.7 mm and the settlement of ground surface was 4.8 mm. In stage 1 (AB), the settlement of foundation increased largely under the applied load. At the end of stage 1 (point B), the settlement of foundation was 6.5 mm and the settlement of ground surface was 5.3 mm. In stage 2 (BCD), the applied load was increased 15 % current load of stage 1. In undrained condition (BC), the settlement of foundation increased 0.5 mm and the settlement of ground surface increased lightly. At point C, the total settlement of foundation was 7 mm while the total settlement of ground surface was 5.4 mm. However, in drained condition (CD), the increase of ground surface settlement was larger than the increase of foundation settlement. For example, ground surface settlement increased about 5.5 mm while the settlement of raft foundation increased about 0.7 mm in a period of 25 minutes of drained condition. At the end of test (point D), the final settlement of foundation was 7.7 mm and the settlement of ground surface was 10.9 mm.

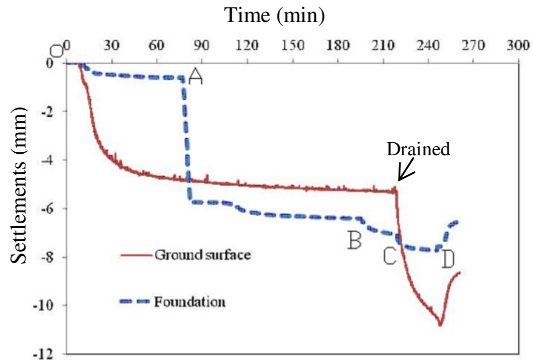


Fig. 14 Settlements of foundation and ground surface with time in case 2

Fig. 15 shows the relationship between foundation settlement which was normalized by raft thickness T_r and applied load which was normalized by undrained shear strength S_u for both cases 1 and case 2. It is noticed that the settlement of the foundation caused by prepared stage was ignored in some figures (from Fig.15 to Fig.18). When the piles were added to the foundation, the settlement of the foundation decreased significantly. In other words, the bearing capacity of piled raft foundation increased remarkably. As shown in Fig.15, at a settlement of 32 % raft thickness (4.8mm), the bearing capacity of piled raft foundation was 4.2 times larger than the bearing capacity of raft foundation. It confirms the effective of piles in reducing settlement for piled raft foundation in undrained condition [11]. In drained condition, the bear capacity of the foundation was also improved appreciably. For example, at the settlement of 45 % raft thickness (6.8 mm), the bearing capacity of piled raft foundation was 5.1 times larger than the bearing capacity of raft foundation.

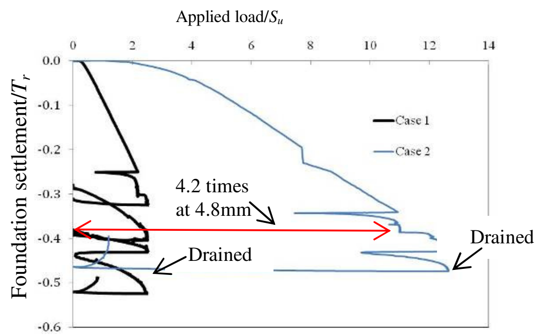


Fig. 15 Foundation settlements/Raft thickness versus applied load/ undrained shear strength

Fig.16 presents the relationship between foundation settlement and ground surface settlement. It revealed that both raft and piled raft foundations continued to settle as ground surface settlement increased. However, regarded to the effect of ground surface settlement, settlement of raft foundation was more affected than settlement of piled raft foundation.

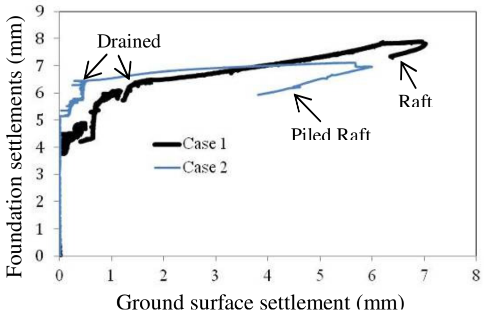


Fig. 16 Foundation settlements versus ground surface settlement

Piled load share is calculated by equation (1):

$$\alpha = \frac{\sum Q}{\sum P_i} \quad (1)$$

Where α is piled load share (%)
Q is the applied load (N)
P_i is the load carried by pile i (N)

Fig. 17 shows the variation of piled load share with normalized settlement of foundation in case 2. Piled load share generally decreased during the settlement process of the foundation in both undrained and drained conditions. The mechanism of the change of piled load share in case 2 could be explained as below.

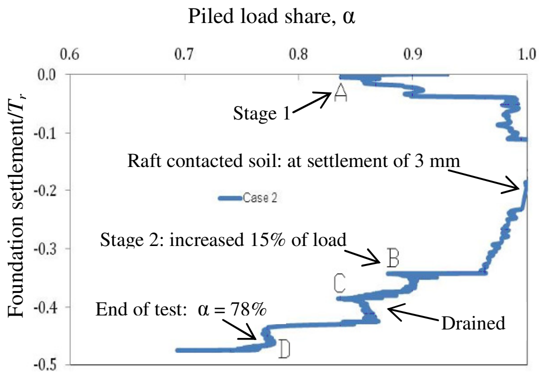


Fig. 17 Foundation settlements/raft thickness versus piled load share in case 2

In stage 1 (AB), the applied load was firstly carried by the piles as the raft did not contact with the ground surface. Therefore, piled load share and settlement of foundation increased. At the settlement of about 20 % raft thickness (3 mm), the raft started to contact with the soil and it shared the load with the piles. Piled load share gradually decreased to point B. It was noticed that, piled load share reduced during the consolidation process of the soil in stage 1.

In stage 2 (BCD), when the load was increased 15 % previous load (BC), foundation settlement increased. Piled load share lightly increased and then reduced gradually during consolidation process of the soil. When the soil was drained at point C, the foundation settled and piled load share had an increase. After that, piled load share reduced to point D along with the consolidation process of the soil. At the end of test, piled load share was about 78 %.

Compared to undrained condition (BC), the decrease of piled load share in drained condition (CD) was more remarkable. When ground settlement occurred, piled load share decreases. It means that the contribution of the piles was decreased in groundwater pumping condition.

The change of piled load share with time in case 2 is shown in Fig.18. The piled load share was rapidly decreased when the drain condition was started. An amount of about 15% of piled load share was reduced in a period of 25 minutes of drained condition.

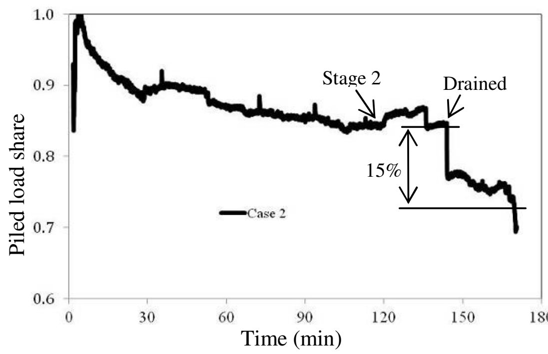


Fig. 18 The change of piled load share with time in case 2

B. Additional results

For checking soil conditions during the test, additional results are also presented in this paper. These results consist of change of pore water pressure in the soil, variation of air pressure in water tank and distribution of contact pressure under the raft during centrifuge tests.

Fig.19 and Fig.20 present the change of pore water pressure with time in case 1 and case 2 respectively. The values of pore pressure transducers at the bottom soil were around 2 times the values at the middle soil in both case 1 and case 2. When the applied load was applied by displacement control method, the load was firstly carried by the water in the soil. Then the applied load was transferred to the soil structures during dissipation of excess pore water pressure and the settlement of the soil increased.

Fig.21 and Fig.22 show the variation of air pressures in water tank in cases 1 and case 2 respectively. The air pressure in the water tank increased up to the values of 6 kPa because of increasing gravity in prepared stage and was constantly kept at that value during stage 1 and stage 2.

The distribution of contact pressure under the raft foundation in case 1 is presented in Fig.23. It could be remarked that the pressure at the center was larger than the pressure at the corner. Unfortunately, data of contact pressure under the raft in case 2 was lost during the test.

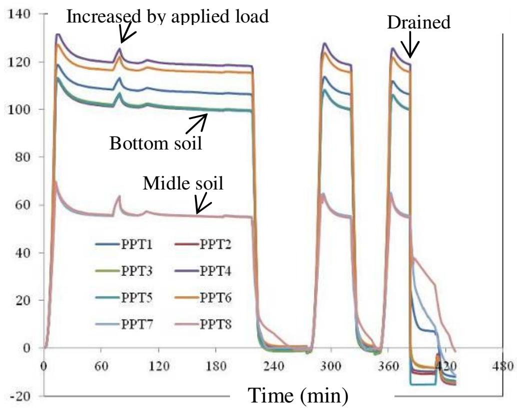


Fig. 19 The change of pore water pressure with time in case 1

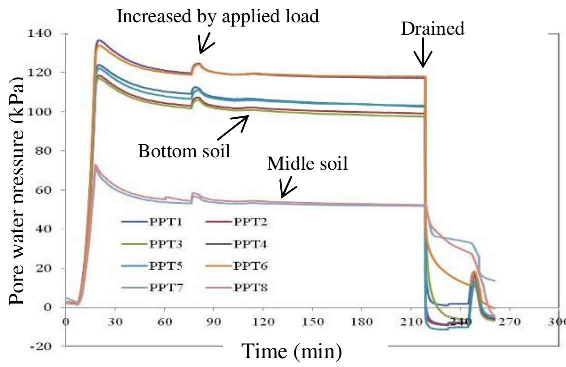


Fig. 20 The change of pore water pressure with time in case 2

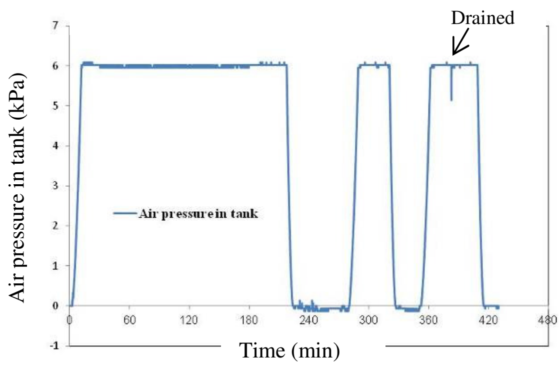


Fig. 21 The variation of air pressure in tank with time in case 1

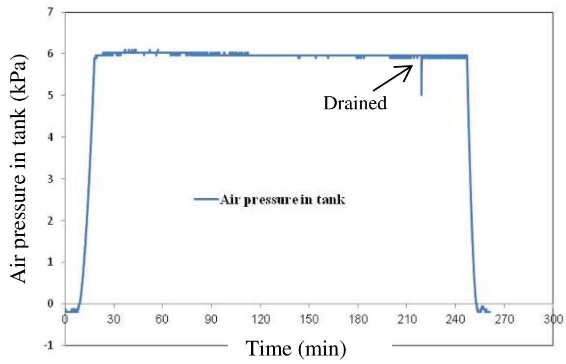


Fig. 22 The variation of air pressure in tank with time in case 2

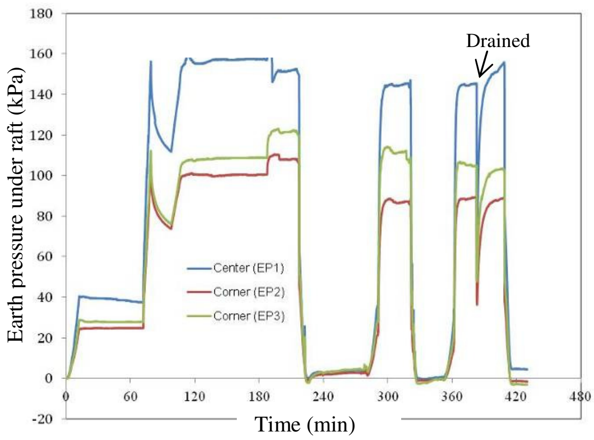


Fig. 23 Distribution of earth pressure under raft with time in case 1

IV. Conclusion

Based on the testing results, effects of ground subsidence on raft and piled raft foundations can be evaluated as below:

1. Settlement of the foundations is significantly increased and raft foundation is more affected than piled raft foundation.
2. Piled load share is decreased rapidly.
3. Effectiveness of piles in reducing foundation settlement is decreased.

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