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Centrifuge Model Tests on Settlement Controlling of Piled Raft Foundation in High-Rise Building

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ABSTRACT

In the design of piled raft foundations, the control of total and differential settlements is crucial. Based on centrifuge tests, this study presents a feasibility of a fairly optimal pile arrangement scheme for reducing total and differential settlements. Two models of piled raft foundations having the same flexible raft and number of piles, uniform pile arrangement and concentrated pile arrangement respectively, were designed for centrifuge tests. The settlements of two rafts were monitored and compared to illustrate the ability of reducing total and differential settlements of the case of the concentrated pile arrangement. The results show that a piled raft foundation with a concentrated pile arrangement can effectively decrease the total and differential settlements in comparison with the one having uniform pile arrangement.

INTRODUCTION

In most structures, the control of total and differential settlements is very important. In particular, differential settlements can have negative effects on a superstructure by causing an increase in the internal stress and in consequence reducing the building service life. Thus, restrictions within allowable limits are necessary. Among the various types of foundations used at present, the piled raft foundation is widely adopted as an effective total and differential settlements reducer. This foundation system consists of piles, raft and soil, with the piles playing the main role in reducing settlements. From an economical point of view, however, the settlement of this foundation should be controlled for an economical design while still satisfying an acceptable level.

There are various mechanical properties that affect the total and differential settlements of a piled raft foundation, such as the loading condition, shape and size of the raft, diameter and length of the piles, the number of piles, the pile spacing, the relative stiffness between the raft and subsoil, and the pile arrangement scheme. These properties need to be considered in the calculation and design of a piled raft foundation. Fleming et al. (1992) and Randolph (1994) proposed the use of a pile group only in the central area of a flexible raft to achieve minimal differential settlement. This concept

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was verified by Horikoshi and Randolph (1996) through a set of centrifuge model tests. Moreover, Horikoshi and Randolph (1998) and Poulos (2001) investigated that increasing the raft stiffness will reduce effectively the differential settlement. Kim et al. (2001) proposed that the differential settlement of piled rafts depending on the load type (i.e., a uniform distributed load, line loads and concentrated loads), and that the method of pile arrangement for minimizing the differential settlement also depends on the load type. Unfortunately, there is no experimental study to verify this concept. As a practical design, Messeturm tower in Frankfurt am Main was designed using a piled raft foundation which has more piles arranged near the edges of the raft at the diaphragm positions (Katzenbach et al. 2005). Nevertheless, there is no measured data or detailed research regarding the ability to reduce the differential settlement in this pile arrangement scheme.

Previous studies have shown that the relative raft-soil stiffness and the pile arrangements strongly affect the total settlement and especially the differential settlement. These two properties need to be considered rigorously, especially with concentrated loads, which is the typical load type in high-rise buildings. Conventionally, the piles are placed uniformly with considering a reasonable amount of pile spacing and cover the entire raft area. However, this pile placing method does not provide a great benefit when seeking to reduce the total and differential settlements for the foundation. Thus, to satisfy the allowable limits, increasing number of piles is necessary, though this increases the construction cost. Alternatively, piles can be placed in a concentrated configuration near the loading points (column positions).

To view the feasibility of the concentrated pile arrangement for reducing total and differential settlements, two centrifuge tests were performed in this study, which involved two piled raft models, a 16-pile raft with a uniform pile arrangement and a 16-pile raft with a concentrated pile arrangement. The type of applied load is a concentrated load consisting of four column loads and the rafts are flexible. The settlements of the rafts in both cases were monitored and compared to each other to view clearly how much settlement and bending moment were reduced when using the concentrated pile arrangement scheme.

EXPERIMENTAL SET-UP AND TEST PROCEDURE

KOCED geotechnical centrifuge

The model tests were performed in the KOCED 240g-ton geotechnical centrifuge at KAIST (Korea Advanced Institute of Science and Technology) in Korea. The maximum capacity of this beam centrifuge at KAIST, with a 5m radius, is 2400kg for up to 100g of centrifugal acceleration and 1,300kg at 130g of maximum centrifugal acceleration. The detailed specifications of the centrifuge equipment can be found in Kim et al. (2007).

Model definition and test program

The physical model reproduces a piled raft foundation having the raft supported by sixteen closed-end piles resting on dry homogeneous silica sand. A centrifugal acceleration factor of N = 50g is used in this study. Two models are used; these are referred to here as model 1 and model 2. Model 1 is a piled raft model consisting of a flexible raft supported by sixteen piles. The piles are placed uniformly four by four with a pile spacing of 100mm (5m in the prototype scale). Model 2 is a piled raft model also consisting of a flexible raft having the same thickness and size as the model 1. It is supported by sixteen piles. These piles are placed densely at the column positions with a pile spacing of 48mm (2.4m in the prototype scale). Details of the pile placing are shown in Figures 1.

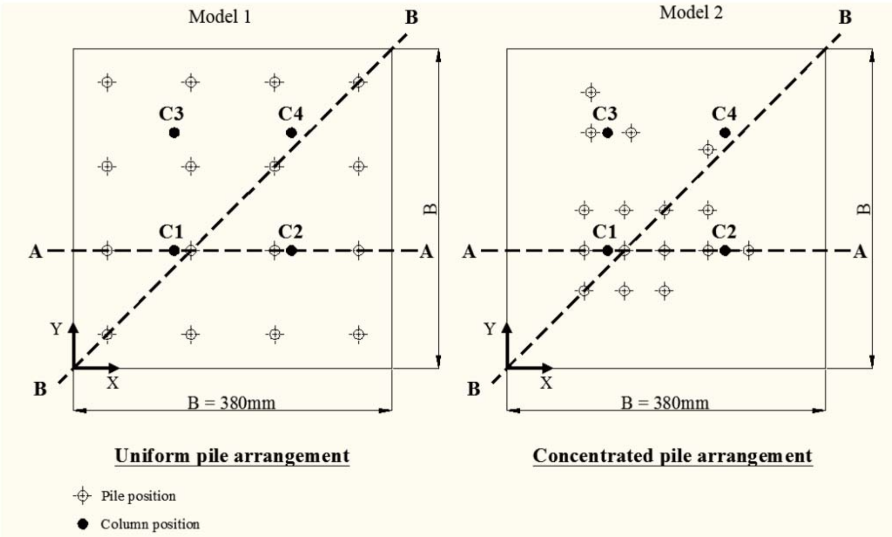

Figure 1. Pile, column, cross section arrangement

The settlements of the rafts are monitored by means of eight linear displacement transducers (LVDT) along two cross-sections, A-A and B-B. The position of LVDTs is shown in Figure 2. Four columns were used to reproduce point loads on the foundation models. The bottom parts of the columns are attached rigidly to the raft and the upper parts are fixed rigidly with the slab connected to the loading equipment. When the loading equipment applies load to the slab, the load is transmitted to four columns, and then transmitted to the raft through four column positions. The transmitted axial load for each column was measured by a column load cell attached at the bottom of each column. Details of the loading system and the applied load positions are shown in Figure 3.

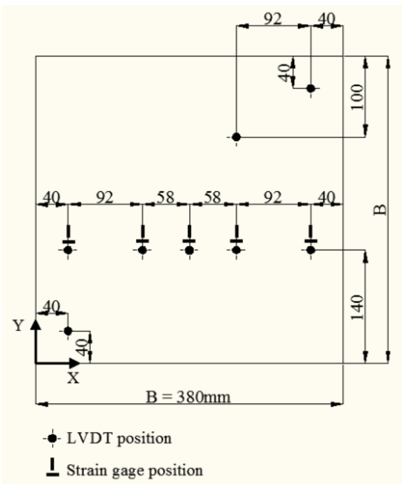

Figure 2. LVDT and strain gage positions

The soil was housed in a rigid circular strong model box with an internal diameter of 900mm and a height of 700mm. The soil surface was located 350mm above the bottom of the container to ensure that the container bottom does not hinder the settlement of the foundation model. The test set-up of the model is shown in Figure 3, and Table 1 summarizes the details of the model size in the model scale.

Table 1. Model dimensions
Centrifugal acceleration N = 50g; Dimension in mm

Parameters	**Model 1**	**Model 2**
Raft thickness (t_r)	8	
Raft side (B)	380	
Plate side	180	
Plate thickness	8	
Pile length (L)	250	
Pile diameter (d)	12	
Column length	60	
Column diameter	12	
Soil depth	350	
Container diameter	900	
Container height	700	
No. of piles	16	
D_r of soil (%)	40	
Pile spacing	100	48

Test soil

Silica sand, with a particle mean diameter D_{50} = 0.22mm, the uniformity coefficient C_U = 1.96 and classified as SP (according to the Unified Soil Classification System), was used for all centrifuge tests. Tri-axial drained tests were performed to obtain the characteristics of the tested soils, which have a relative density D_R of approximately *40%*. The test results are presented in Table 2.

Table 2. Silica sand parameters

Relative Density	Confinement Pressure	Depth (m)	E (Mpa) $\varepsilon >$ 0.2%	Peak friction angle (ϕ)	Critical state friction angle (ϕ_{cr})
Loose State Dr=40% (γ_d=1.37 t/m^3)	50 kPa	3.8	8.47	40^o	33.5^o
	100 kPa	7.6	13.33		
	200 kPa	15.2	36.84		

The dry sand sample with a relative density D_R of about 40% (loose state) was prepared by the air pluvial method using an automatic sand-rainer. Detail of the method of controlling relative density can be found in Kim and Kim (2010). The spreader was passed repeatedly over a circular strong model box (900mm in a diameter) until the thickness of the sand layer was approximately 350mm (17.5m in the prototype scale).

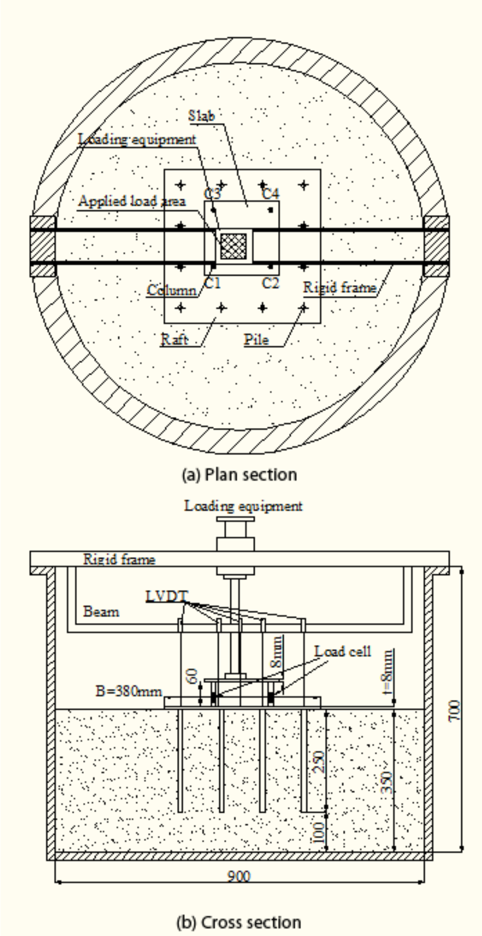

Figure 3. Typical test model set-up for load test on the piled raft model

Relative raft-soil stiffness

The relative raft-soil stiffness significantly influences the differential settlement of a piled raft foundation. When the stiffness of the raft is large, the differential settlement of a piled raft is small, and vice versa. Thus, the determination of the raft thickness is very important. Horikoshi and Randolph (1998) proposed the following equation to estimate the relative flexibility of rectangular rafts:

$$K_{rs} = 5.57 \frac{E_r}{E_s} \frac{1-\upsilon_s^2}{1-\upsilon_r^2} \left(\frac{B}{L}\right)^{\alpha} \left(\frac{t_r}{L}\right)^3 \quad (1)$$

where E_r, E_s = Young's modulus of the raft and the soil, respectively; υ_r, υ_s = Poisson's ratio of the raft and the soil, respectively; B, L = the breadth and the length of the raft, respectively; t_r = the thickness of the raft; α = experimental factor ranging from

0.5 to 1.

According to Horikoshi and Randolph, the raft is flexible when K_{rs} ranges from 0.01 to 1.0. In this paper, equation (1) was used to consider the flexibility and to calculate the thickness of the raft models.

Piled raft model

The flexible raft model was made up of aluminium alloy having a square shape of 380mm wide in the model scale (19m in the prototype scale). The raft's thickness was evaluated according to equation (1) with the input parameters of the concrete material (E_r = 2.82E+07kN, υ_r=0.16) and the subsoil (E_s = 8.47E+03kN, υ_s=0.25) derived from Table 2. The value of the thickness in the prototype scale was calculated at about t_r = 0.542m and converted to the model scale of about 8mm, corresponding to K_{rs} = 0.4.

The closed-end model piles were made up of aluminium alloy pipes. The external diameter is D_p = 12mm (0.6m in the prototype scale) and the length is L = 250mm (12.5m in the prototype scale). Sixteen pile models were used in this study and were fixed rigidly to the raft.

The model column was made up of two aluminium alloy pipe segments in order to install a load cell at the bottom part. The load cells measure the axial load transmitted to the columns. The column model has an external diameter D = 12mm and a length L = 60mm.

Test procedure

In this study, the piled raft models were penetrated into the soil at 1g. It should be noticed that the models should be installed in-flight to obtain the prototype capacity correctly. Craig (1984) suggested that if piles are installed at lower accelerations, the pile capacity can be reduced. Nevertheless, the aim of this study is to evaluate the total and differential settlements of a piled raft foundation in a uniform pile arrangement and in a concentrated pile arrangement cases. Differences in pile capacity due to the method of penetration are irrelevant in a qualitative estimation of the settlement. The following test procedures were adopted:

At 1g: a homogeneous soil model was prepared by pluvial deposition into a circular container. The container was then placed into a centrifuge basket and the piled raft model was then installed to the loading equipment and penetrated into the soil until the bottom of the raft reached the soil surface. LVDTs were attached to a holding system of the beam, and core tips were rested directly on the surface of the raft to monitor the raft settlement (Figure 3).

At 50g: After the soil surface settled down completely, the piled raft model was driven into the soil to about 1~2mm to ensure that the raft was in perfect contact with the soil surface (1~2mm is the settlement of the soil surface during the increase of the centrifugal acceleration from 1g to 50g). Then, all sensors were adjusted to null values to eliminate the deformation of the LVDT supporting system. The loading test was then performed. The loading equipment penetrated the model at a rate of 0.04mm per second (the rate of penetration) until a relative displacement $w/D_p \approx 20\%$ was reached, where w is the measured settlement.

RESULT AND DISCUSSION

All results and comparisons are made in the model scale.

Comparison with transmitted column loads

Figure 4 shows a comparison with transmitted axial forces in four columns of two piled raft models. The figure shows that in all models, column C1 receives the largest transmitted axial force and column C4 receives the smallest force. The amount of load transmitted to C4 equals about 35% of that transmitted to C1 as the point of the applied concentrated load is near column C1. This will cause the differential settlement for the piled raft models along section B-B. The load at column C2 is smaller than that at column C1 (about 60% of the load received by C1); this will cause the differential settlement along section A-A. The positions of columns C1, C2, C3 and C4 are presented in Figure 1.

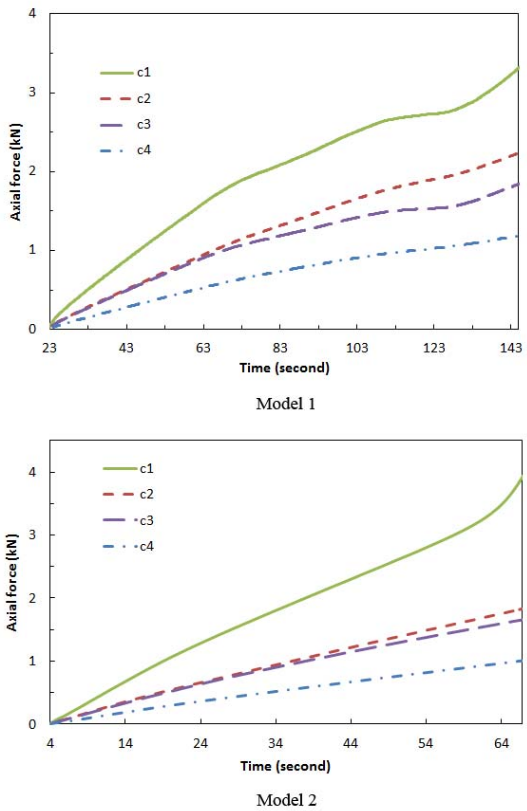

Figure 4. Comparison of the axial forces transmitted to columns

Comparison of the settlement between model 1, model 2

The comparisons of the settlements between two test cases are summarized in Figure 5 and Figure 6. Figure 5 shows the comparison of the settlements along section A-A and Figure 6 presents the settlements along section B-B. The centrifuge test data show the general trend in which the total and differential settlements of the piled raft increase corresponding to the increase of the total applied load. With model 1, the settlement curves have a hyperbolic shape with the maximum settlement point at column C1 (+132mm from the zero point of the X- axis) and the minimum settlement point at the monitored points near column C4 (+340mm from the zero of X- axis). The largest load transmitted to C1 and the smallest transmitted to C4 cause this shape. However, with model 2, at the level of total applied loads of 5kN and 7.5kN, the settlement lines of the raft are fairly straight, as the pile group near column C1 helps to reduce the differential settlement considerably.

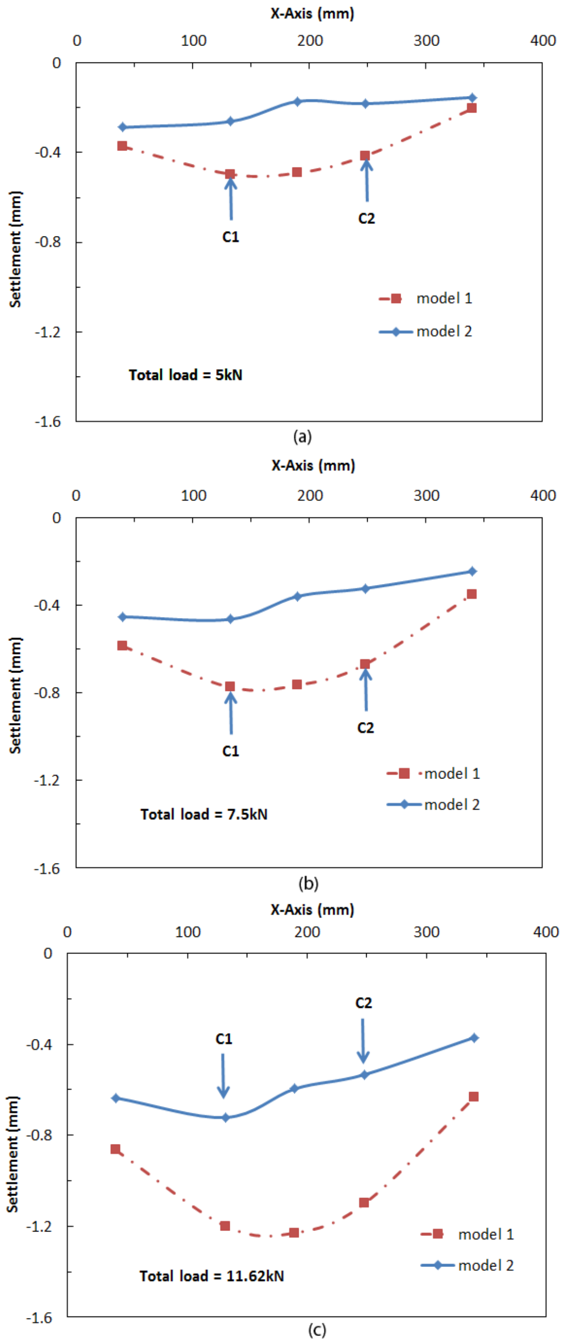

Figure 5. Comparison of the settlement along section A-A of the rafts between two models

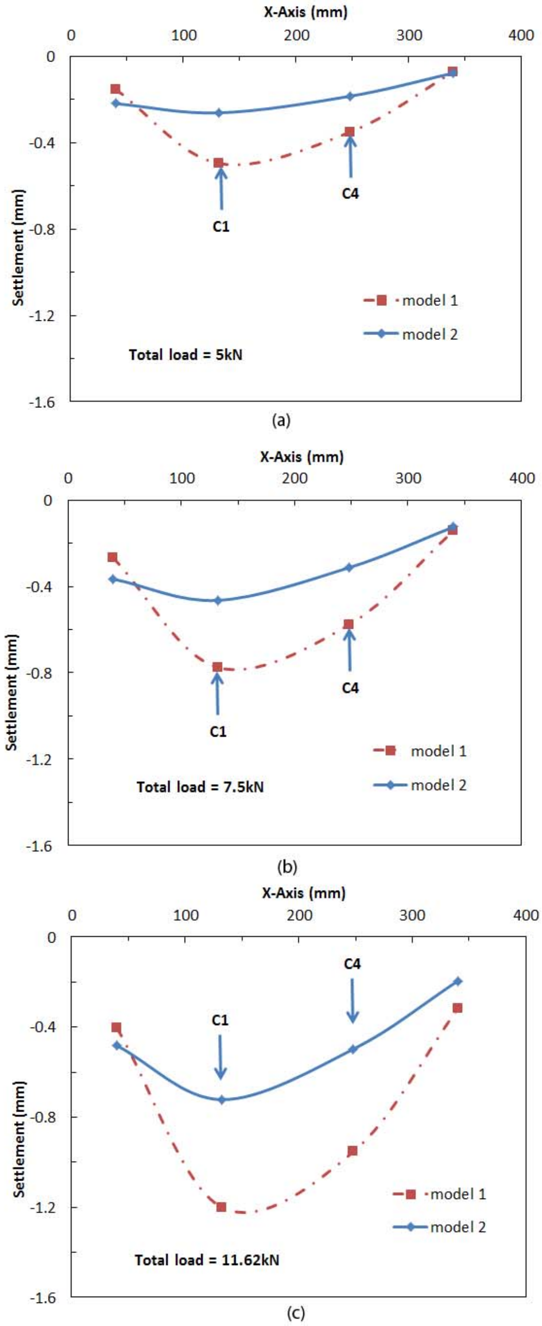

Figure 6. Comparison of the settlement along section B-B of the rafts between two models

In addition, the centrifuge results show that the total and differential settlements of the piled raft in model 2 are much smaller than that of model 1. When the total load reaches 11.62kN, the total and differential settlements of model 2 are approximately 60% in comparison with model 1. This illustrates that the potential for reducing total and differential settlements of the concentrated pile arrangement scheme is considerable.

There are several ways to explain how the optimal pile arrangement scheme can reduce the total and differential settlements considerably. First, when the pile spacing has a reasonable value, the interaction among the piles increases, causing an increase of the supporting capacity of the pile group and therefore reducing the settlement of the raft at the region of the pile group. Second, it can utilize the capacity of the raft at regions subjected to small applied loads. At these regions, with or without the presence of piles, the raft can support the amount of loads subjected to it and its settlement remains at an acceptable value. As shown in the centrifuge test, at the region of column C4, the measured load transmitted to the raft is much smaller than that of the other columns. Therefore, only one pile was used.

Comparison of the differential settlements at column positions

Figure 7 presents the comparison of the total load-differential settlement curves between two tested models. Here, the differential settlements are calculated from the settlement difference between the maximum settlement column position (column C1) and the minimum settlement column position (column C4). The result shows that the curves of the concentrated pile arrangement scheme are lower than those of the uniform pile arrangement scheme because the differential settlement amount is smaller than in the uniform case. All two curves converge when the total load becomes large; for the column having the maximum transmitted load, the capacity is mainly achieved by the end bearing as the settlement at this column increases.

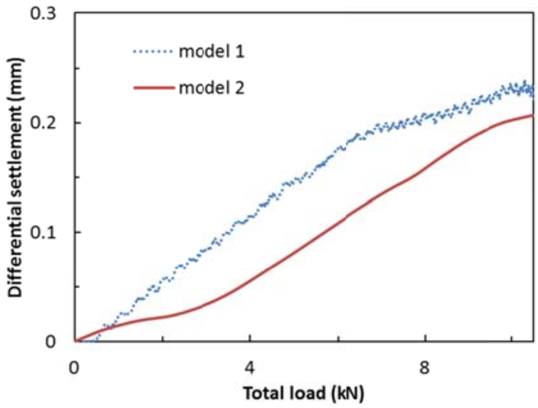

Figure 7. Comparison of the total load-differential settlement curves between column C1 and column C4

CONCLUSION

This paper presents the feasibility of the concentrated pile arrangement for reducing the total and differential settlements of piled raft foundations through experimental study. In total, two main centrifuge tests were performed to observe the settlement of piled rafts on dry silica sand, and highly consistent results were obtained. The centrifuge test results showed the effect of the concentrated pile arrangement in reducing settlements. This effect becomes more considerable when the total applied load is large. In general, the concentrated pile arrangement case can result in total and differential settlements lower by about 30% to 40% when compared to the uniform pile arrangement case.

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