




Comparative analysis of Piled Raft Foundation System (PRFS) settlements placed on soft soils via geotechnical centrifuge

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Article

Keywords

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Abstract

The use of Piled Raft Foundations Systems (PRFS) has been extended to different types of soils, including soft clay soils. In this type of soil it is possible that, in addition to the consolidation process due to the presence of loads, a subsidence process is generated, associated with variations in pore pressure with depth. In many cases, these variations are associated with the loss of recharge of the aquifers or with the extraction of water from deep soil layers. In this work, the behaviour of some PRFS built on soft clay soils, which are subjected to the double consolidation process, are evaluated, both by loading and by the extraction of water from deep soil layers. The research is based on the implementation of reduced-scale models in a geotechnical centrifuge; the influence of the separation and number of piles on the deformation or settlement of the system is analysed. It is shown that, normally, groups of piles with greater separation control settlement more effectively. However, the settlements are greater when the soil is subjected to the weight of the structure in addition to a process of depletion of the pore pressure, because the settlement depends on the distribution of the piles, which is described using the Filling Factor (FF).

1. Introduction

The use of Piled Raft Foundation Systems (PRFS) as a foundation system has been extended to different types of soils, including soft clay soils in which consolidation phenomena occur due to load and/or due to changes in the pore pressure condition. The behaviour of PRFS in soils that suffer consolidation due to variations in pore pressure (subsidence) have not been studied comprehensively (Rodríguez-Rincón, 2016).

Cities like Shanghai, Bangkok, Mumbai, Kuala Lumpur, Jakarta, Singapore, Bogotá, and Mexico are underlain by soft clay soils. In these cities, the use of PRFS has been expanded. These systems have presented damage associated with subsidence processes because the normal working conditions of PRFS vary (Banerjee, 2009; Bareño & Rodríguez-Rincon, 1999). In piles built under these conditions, negative friction can be generated, which induces additional vertical loads and settlements. In extreme conditions, this can lead to pile failure (Leung et al., 2004; Auvinet-Guichard & Rodríguez-Rebolledo, 2017).

In the traditional design approach of PRFS, the raft is able to withstand the imposed loads however, the piles

are additional elements designed to control deformations, especially differential settlements. With more up-to-date approaches, piles are added both to control settlement and to support part of the load imposed on the system; the PRFS is a geotechnical composition of three elements: raft, piles and soil (Burland, 1977).

Rodríguez-Rebolledo et al. (2015) mentioned that, worldwide, several field studies have been carried out on individual piles that are arranged in a soft soil and consolidated by reducing pore pressures. However, only some of these consider the use of piles working only by friction and almost none of them consider the three-dimensional effects. Rodríguez-Rincón (2016) indicated that some studies have been carried out on groups of piles and PRFS that present piles working by friction, but they do not consider the variations that can occur due to the extraction of water from deep layers and the consequent variations in pore pressure.

This research aims to advance the understanding and evaluation of the influence of subsidence (by extracting water from deep layers) on PRFS that are built on soft soils and include piles that work by shaft friction. This type of

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knowledge will allow the adjustment of analytical and numerical models that better represent the behaviour of this type of foundation, under the conditions presented here.

The main characteristics and the results obtained from experimental work are presented; this was carried out by implementing 10 models of PRFS on a reduced scale and tested in two types of geotechnical centrifuge. As a result of the investigation, the influence of the number, separation and distribution of the piles on the collapse of the PRFS (when the medium is consolidated) was determined, both by the weight of the structure and by the reduction of the pore pressure due to the extraction of water from deep permeable layers.

2. Background and concepts

2.1 Piled Raft Foundations Systems (PRFS)

One of the first practical works using the PRFS concept was developed by Zeevaert (1957), using a pile group system working by friction, with the aim of reducing the settlements of a 43-storey building (Torre Latinoamericana) placed in the lacustrine clays of Mexico City. From a theoretical point of view, one of the first works that includes the concept of a shallow foundation supported on piles is attributed to Poulos in the 1960s. In this work, the author concluded that the settlement of very long piles ($L/d > 25$) is controlled by the soil-raft contact (Poulos & Mattes, 1971).

According to Janda et al. (2009), the PRFS corresponds to a three-element geotechnical composition in which two structural components (piles and raft) interact with each other and with the surrounding soil, to support the loads (vertical, horizontal or moments) that come from the superstructure. This system can be designed to present an adequate Safety Factor according to the relevant state limits, guarantee its load capacity, guarantee the control of settlements, or guarantee the two conditions simultaneously (Mandolini et al., 2013).

In the traditional design process of groups of piles, the number of piles is determined by dividing the total load placed

on the group by the individual load capacity, considering a minimum Safety Factor (average) for all piles. When the influence of group stiffness is analysed, in this case, it is found that the peripheral piles support more load, which generates an increase in the number of piles to guarantee the minimum safety factor for all piles (Sales et al., 2002).

The load-settlement curve (Figure 1) may not be linear under design conditions however, the system has an adequate Safety Factor and the maximum allowable settlement criterion is met. Thus, the design represented by curve 3 in Figure 1 is acceptable and will likely be less expensive than the designs represented by curves 1 and 2.

According to Chow (2007), in PRFS design it is necessary to understand the load transfer mechanism of the raft to the piles and to the soil, considering:

- The behaviour of the raft, including settlements, moments and proportion of load assumed by this element;
- The transfer mechanism involves a complex interaction between the raft and the piles, in addition to the surrounding soil, taking into account that the stress-strain response of the system is controlled by several factors, such as soil properties, group geometry, the type of load and the execution process.

In the literature, some authors (e.g. Poulos, 1993; Durán, 2003), established load proportions assumed by the raft (up to 80% of the load) and the piles (up to 20%), under external load conditions and without variation of the soil water conditions. Mandolini et al. (2013) presented a graph (Figure 2) in which the variation of the proportion of total load taken by the raft is established as a function of the Filling Factor (FF). The FF establishes that the behaviour of a PRFS depends on parameters related to both the piles and the raft, as defined by Equation 1.

$$FF = \frac{A_G d}{A_R s} \quad (1)$$

where A_G is the piles group area, defined by De Sanctis et al. (2002), as shown in Equation 2.

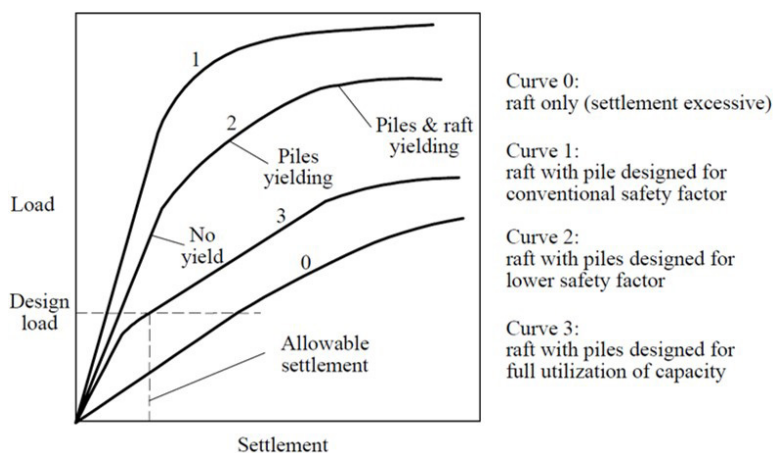


Figure 1. Load settlement curves for piled rafts according to various design philosophies (adapted from Van Impe, 2001).

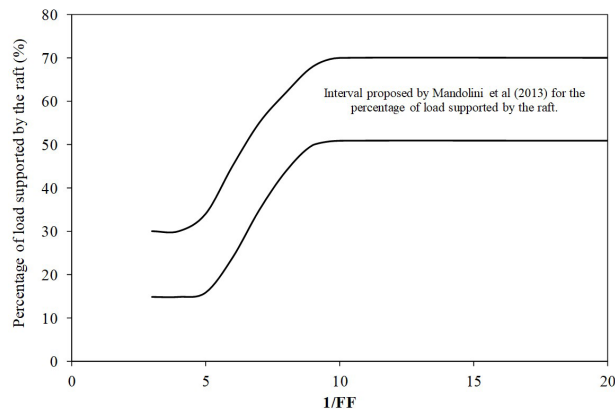


Figure 2. Proportion of load assumed by the raft (adapted from Mandolini et al., 2013).

$$A_G = \left[\left(\sqrt{N_p} - 1 \right) s \right]^2 \quad (2)$$

where A_R is the raft area; s the piles spacing; d the pile diameter and N_p the number of piles in the group.

Determining the settlement of the PRFS turns out to be the critical point (Chung Nguyen et al., 2013). One way to evaluate the influence of the inclusion of piles under a raft was proposed by Bajad & Sahu (2008), through the settlement reduction ratio (S_r) defined in Equation 3.

$$S_r = \frac{d_{ri} - d_r}{d_{ri}} \quad (3)$$

According to the authors, this parameter makes it possible to relate the settlement of the raft without piles (d_{ri}) and the settlement of the PRFS (d_r). Thus, when the settlement of the piles increases, the raft supports a greater load. In this case, the piles act as elements that reduce settlement. If the load taken by the piles increases, this increase is low and the pile group can take up to 60% of the load. The settlement in the system decreases when the number of piles increases; there is a critical settlement value from which the piles do not contribute to the resistance of the system.

2.2 PRFS in soft soils

For Poulos & Davis (1980), the most suitable sites for PRFS to be implemented are those where relatively rigid clays, dense sands and stratigraphic profiles without soft strata prevail below the tip of the piles. Poulos (1993) presented some situations in which the use of PRFS would not be recommended, including profiles of soils with soft clays or loose sands close to the surface, or those that presented compressible, collapsible or expansive soils.

Balakumar & Anirudhan (2011) mention that the use of PRFS is optimal when they are built on over-consolidated clays with loads from tall buildings, in which the raft is

deepened, generating relief from stress conditions at the edges, which influences the settlements.

In more recent years, the use of PRFS in soft soils has increased in areas where there are soft clays or with different non-rigid material behaviour, just as more research and developments have been presented. Some analytical methods for studying the behaviour of PRFS have been presented by Kuwabara & Poulos (1989), Lee (1993), Teh & Wong (1995), De Sanctis & Mandolini (2006), Roy et al. (2011), and Rodríguez-Rebolledo & Auvinet (2019), among others. These have focused on the influence of negative friction on induced loads (drag loads) on the piles, due to the consolidation of soft soils.

Numerical methods were implemented by Katzenbach et al. (1998), Chow et al. (2001), Reul (2002), Lee et al. (2002), Lee & Ng (2004), El-Mossallamy (2011), Cho et al. (2012), Rodríguez-Rebolledo et al. (2015), Khanmohammadi & Fakharian (2018) and Mali & Singh (2018), among others. These studies focused on analysing the soil-structure interaction, the load distribution, the potential failure surfaces along the shaft and the settlements of the PRFS or group of piles. They used material response models that were not the usual Mohr-Coulomb type, including the influence of the subsidence phenomenon on the behaviour of the PRFS or groups analysed.

In Brazil, Cunha et al. (2000), Sales (2000) and Ayala (2013), have shown that PRFS can be implemented in collapsible clayey soils, such as those in the city of Brasilia, presenting adequate behaviour, in terms of load support and settlement control, decreasing the costs of the foundations. With a study that analysed the behaviour of PRFS in the city of Bogotá, Durán (2003) concluded that these systems present an adequate response when piles that work by friction are included to support the secondary compression and subsidence processes generated by the change in the pore pressure conditions.

With 1g scale models, Shibata et al. (1982), Ergun & Sonmez (1995) and Bajad & Sahu (2008) analysed the distribution of loads and settlements in PRFS or groups of piles subjected to vertical loads and arranged on soft soils, including the influence of negative friction on their behaviour.

Thaier & Jessberger (1991) presented the results of an experimental model on a 50g scale, evaluating the effect of the number of piles, and their diameter and length, on the behaviour of a PRFS subjected to axial load. They concluded that the geometry is one of the variables that most influences the behaviour of the system, when it is placed on soft clay-type material. Horikoshi & Randolph (1996) used a 100g model to evaluate the bearing capacity of a PRFS in soft soils and the effect of lateral confinement, for variable vertical loads. Tran et al. (2012) analysed the influence of subsidence in a PRFS system using a 50g scale model, concluding that the load supported by the piles, as well as their effectiveness as settlement controllers, decreased with time as a function of the subsidence processes.

Cui et al. (2010) mentioned that few studies have been carried out to analyse the three-dimensional and time-dependent behaviour of PRFS, due to the fact that it is easy to represent the variation of pore pressure in the soil. Normally, linear stress-strain behaviour is assumed, which does not correspond to the real behaviour of the system, making it necessary to develop more realistic models that reproduce these interaction phenomena and the effects of subsidence.

3. Experimental program

In this research, we analysed the effects of the consolidation of a soil by an external load and by variations in pore pressure due to the extraction of water from deep soil layers, in the response of a PRFS. Specifically, the response of the PRFS is evaluated by the settlements measured on the raft and in the soil near the raft.

3.1 Testing facilities

The testing facilities used in this research consisted of two beam geotechnical centrifuges with the characteristics shown in Table 1 and Figure 3 (the largest capacity equipment) and in Table 2 and Figure 4 (the smallest equipment), The facilities were located at the Geotechnical Models Laboratory of Los Andes University in Bogota, Colombia.

3.2 Scale, materials, and geometry of the PRFS models

To scale the models, is necessary to guarantee the similarity between models and prototypes based on the flexural modulus, as shown in the Equation 4 (Taylor, 1995).

$$E_m^{mm} I_m^{mm} = E_m^c I_m^c \tag{4}$$

where E_m^{mm} is the elastic modulus of the material in the model; E_m^c is the elastic modulus of concrete; $I_m = (bt^3)/12$ is the moment of inertia, where b is the base of the element and t is the thickness of the element.

As a specific prototype was not taken, it was sought to guarantee that at least the values of the modulus (E) were consistent with the typical values recommended in the literature. Equation 4 was applied to the raft, as it was the main element subjected to flexural stress, for all of the other elements, conversion of the dimensions was proportional to the scale factor.

Table 1. Large geotechnical centrifuge characteristics.

Turning radius (m)	1.90
Model boxes dimensions (cm)	40 × 50 × 60
Gravitational field maximum (g)	200
Maximum model weight (kN)	4.0
Nominal power (HP)	400
Channels for data acquisition	50

Note: g = earth's gravity; 1HP = 745.7 W.

Table 2. Small geotechnical centrifuge characteristics.

Turning radius (m)	0.56
Model boxes dimensions (cm)	7 × 14 × 12
Gravitational field maximum	300g
Maximum model weight (N)	50
Nominal power (HP)	3
Channels for data acquisition	40

Note: g = earth's gravity; 1HP = 745.7 W.

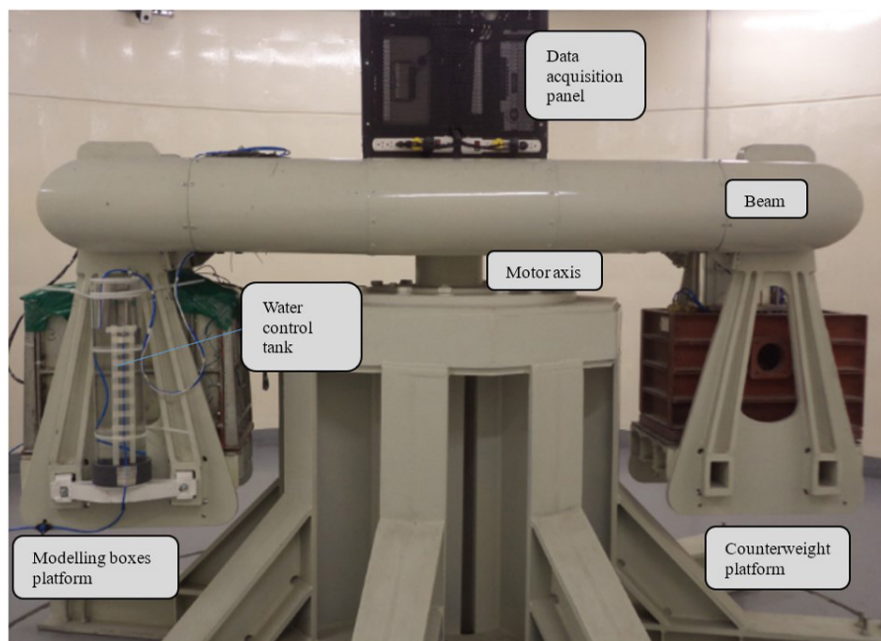


Figure 3. Large beam geotechnical centrifuge.

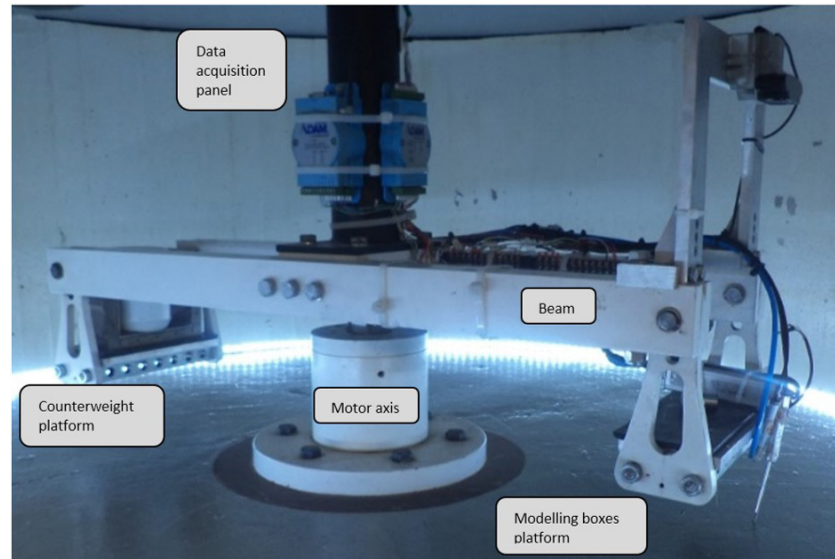


Figure 4. Small beam geotechnical centrifuge.

Table 3. Dimensions and materials for model elements and prototype equivalences.

Element	Parameter	---- 70g ----		---- 200g ----	
		Model characteristic	Prototype characteristic (equivalent)	Model characteristic	Prototype characteristic (equivalent)
Raft	Material	Aluminium	Concrete	Acrylic	Concrete
	Thickness, e_R	13 mm	1.147 m	9 mm	1.0 m
	*Elasticity modulus, E	70000 MPa	35000 MPa	6000 MPa	35000 MPa
	Width, B	200 mm	14 m	40 mm	8 m
	Length, L	200 mm	14 m	40 mm	8 m
Piles	Material	Aluminium	Concrete	Wood	Concrete
	Diameter, D	9 mm	63 cm	3 mm	63 cm
	*Elasticity modulus, E	70000 MPa	30000 MPa	18000 MPa	30000 MPa
	Length, L	320 mm	22.4 m	80 mm	16.0 m

*Parameter value based on supplier's information and the literature.

Taking the Equation 4 and considering a unit base width, the dimensions of the raft-type elements are determined from Equation 5.

$$t_p^c = \frac{t_m^{mm} n_l}{\sqrt[3]{\frac{E_m^c}{E_m^{mm}}}} \quad (5)$$

where t_p^c is the concrete thickness in the prototype, t_m^{mm} is the thickness of the element made from the corresponding material in the model, n_l is the scale factor, E_m^{mm} is the elastic modulus of the material in the model, and E_m^c is the elastic modulus of concrete. Table 3 presents the dimensions and equivalences between the models and the prototypes.

The scale factor in this work was selected based on the dimensions of the modelling boxes, being 70 times the value of the force of gravity (70g) for the models to be implemented in the larger centrifuge, and 200 times the force of gravity (200g) for the models in the smallest centrifuge.

Table 3 presents the dimensions and equivalences between the models and prototypes.

The models included piles with 3×3 , 4×4 and 5×5 group distributions under the raft, with distributions centred (C) or distributed over the entire raft area (T). The models are specified in Table 4, where the denomination M corresponds to the largest models (at 70g scale) and the denomination m corresponds to the smallest models (at 200g scale).

3.3 Soil profile

According to the principles of geotechnical modelling, the model must duplicate the factors that influence the soil response: level of stresses and resistance. In the case of clays, it is necessary to control the void ratio and the pressure applied in manufacturing the soil, to comply with these requirements.

The soil profile selected to represent the behaviour of soft clay soils was that proposed by Rincón & Rodríguez-Rincón (2001), which corresponds to a clay profile of variable

Table 4. Pile distribution and geometric configuration of the models.

Model	Raft dimensions (cm × cm)	Raft thickness (cm)	Piles diameter (cm)	Piles length (cm)	Distribution	Spacing (cm)	Piles number
M3	20 × 20	1.3	0.9	32	3 × 3 C	1.8	9
M4	20 × 20	1.3	0.9	32	4 × 4 C	1.8	16
M6	20 × 20	1.3	0.9	32	3 × 3 T	8.1	9
m1	4 × 4	0.9	s/p	s/p	s/p	s/p	s/p
m2	4 × 4	0.9	0.3	8	3 × 3 C	0.6	9
m3	4 × 4	0.9	0.3	8	4 × 4 C	0.6	16
m4	4 × 4	0.9	0.3	8	5 × 5 C	0.6	25
m5	4 × 4	0.9	0.3	8	3 × 3 T	1.7	9
m6	4 × 4	0.9	0.3	8	4 × 4 T	1.13	16
m7	4 × 4	0.9	0.3	8	5 × 5 T	0.85	25

Table 5. Kaolin properties.

Parameter	Value
Specific gravity, G_s	2.68
Liquid limit, w_L (%)	54
Plasticity index, I_p (%)	33
Plasticity limit, w_p (%)	21
Compression index, C_c	0.37
Swelling index, C_s	0.09
Vertical consolidation coefficient, C_v (m^2/s) × 10^{-6}	0.49-0.62

resistance with depth, from 10 kPa at the surface to 40 kPa in the bottom of the thickness to be modelled. This is typical for the city of Bogotá DC. Commercial kaolin was used in the soil profile construction, with the characteristics shown in Table 5. Kaolin characterisation was performed in the laboratory from reconstituted samples.

The soil was manufactured inside or outside the geotechnical centrifuge. In the latter case, it was necessary to perform testing to ensure uniformity of the stress with depth and pore pressures inside the soil (Thaier & Jessberger, 1991; Taylor, 1995; Rincón & Rodríguez-Rincón, 2001; Dallos, 2007). For the present investigation, manufacturing outside the centrifuge field was implemented, executing the procedure presented by Rincón & Rodríguez-Rincón (2001) and described by Rodríguez-Rincón et al. (2020). This procedure consists of manufacturing several layers of soil, starting of a mixture of kaolin with water (slurry with water content of 1.5 times the liquid limit), applying a pressure (or equivalent load) value, based on the load-undrained shear correlation curve determined in laboratory and controlling the degree of consolidation. The samples were manufactured outside the centrifuge (1g), subjecting it to pressures of the same magnitude as the vertical stresses to which it would be subjected when the test was carried out at 70g or 200g.

3.4 Model testing

The objective of this research was to analyse the settlement of PRFS subjected to a double consolidation process. The models were placed inside soil in the modelling

boxes, subjected to an initial consolidation process by an external load and then to a double consolidation process, by an external load and extraction of water from deep layers.

To guarantee outflow of water during the testing (or ‘flights’) of the modelling boxes, for the two scales used, a filter material was placed in the lower part. In the case of the 70g scale models, this corresponded to a sand filter embedded in layers of geotextile and, for the 200g scale models, the filter comprised porous stone, approximately 0.5 cm in thickness. For the boxes of the larger models (70g), two intermediate 0.7 cm thick filters (sand embedded in filter paper) were implemented throughout the area of the model box, with the objective of reducing testing times, by reducing the effective drain length. For the 200g scale models, these filters were not necessary.

The extraction of water effectively represented the phenomenon of subsidence in soft soils. To carry out this process in the models, the lower part of the modelling boxes had a water outlet connected, internally, to the lower filter material (sand filter or porous stone) and, externally, to a water level control tank (Item 3 in Figure 3). The lower filter materials guaranteed equilibrium pore pressure conditions in the soil, when evaluating the response of PRFS subjected to consolidation due to external load. The function of the external tank was to control the pressure of the water inside the soil or to allow it to escape.

The proposed test stages are outlined in Figure 5, considering that some stop times had to be carried out during the tests (when it was necessary to modify the drainage condition or for the construction of the PRFS in the model), due to the inability to make modifications during the test. The three stages defined for the test correspond to:

- Stage 1 - Self-weight reconsolidation step;
- Stage 2 - Consolidation by load application over the PRFS, keeping the hydraulic external condition (maintaining the water level in the external control tank);
- Stage 3 - Consolidation by load and extraction of water from deep soil layers (lower layer of sand).

During the first two stages of the test, the water level in the external tank was maintained up to the same height as

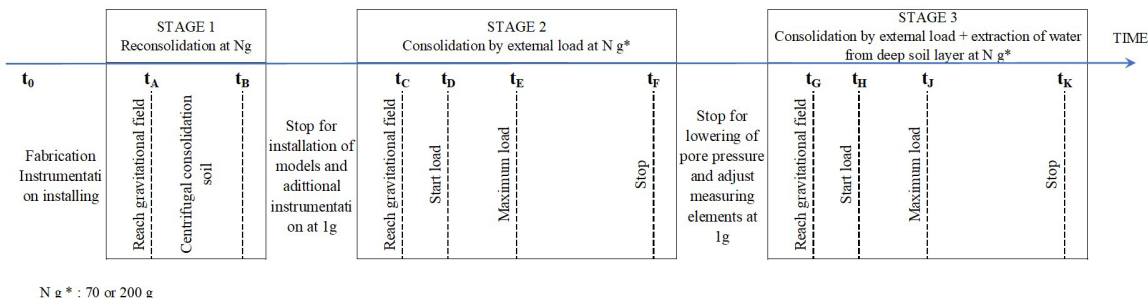


Figure 5. Stages and model's time-line.

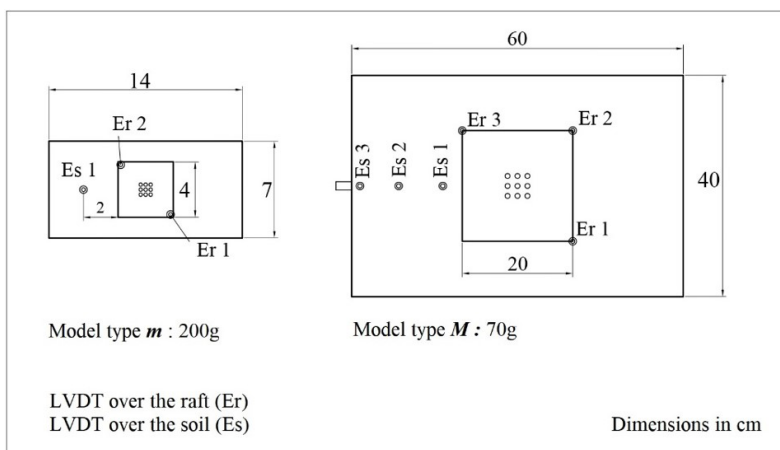


Figure 6. LVDTs distribution in the Model.

Table 6. Testing times.

Activity	Range*	Flight time to 70g Model (h:mim)	Flight time to 200g Model (h:mim)
Model soil preparation	$t_0 - t_A$		
Stage 1	$t_A - t_B$	1:54	1:20
Stop for instrument and model installation	$t_B - t_C$		
Stage 2	$t_C - t_F$	2:54	1:45
Stop for external water tank disconnection	$t_F - t_G$	0:30	0:15
Stage 3	$t_G - t_K$	2:54	1:45

Range*: time ranges referred to Figure 5.

the ground surface in the model, guaranteeing the pressure balance and that the volume changes were generated by the flow of water due to increased stresses.

In the models, to measure the settlements, Linear Variable Differential Transformers (LVDTs) were implemented at various points of the raft and the soil, as shown in Figure 6, also load cells in the two type of models and, pore pressure gauges on the 1:70 scale models. However, this paper focuses on the analysis of the models' settlements. Additionally, from the resistance profile assumed for the soil and through Meyerhoff's bearing capacity equation for a raft without piles, the load value to be applied on the raft was determined. The load was applied by pneumatic actuators and corresponded to 92 kPa (1.46 kN multiplied by the area) for the 70g scale models and 37 kPa (60 N if the area is considered) for the 200g models.

From the values of the vertical consolidation coefficient (C_v) of the material and based on the drainage lengths for each model, the test times that would guarantee a minimum degree of consolidation of 90% were determined. The calculated times are presented in Table 6.

In Table 6 was included a stop between stages. This stopping time was short, compared to the test time, and the soil rebound was controlled. Although the stress conditions may vary with the stop of the test, when the test is restarted, the conditions are recovered elastically. In any case, between stage 2 and stage 3, the modification of the pore pressure condition is carried out, generating that the rebound deformations are less important than the deformation associated with the double process of loading and extraction of water in deep layers.

Table 7. Filling factors to the models (FF).

Parameter	Model								
	M3	M4	m2	M6	m3	m5	m4	m6	m7
Diameter - d (cm)	63	63	60	63	60	60	60	60	60
Piles number - N_p	9	16	9	9	16	9	25	16	25
Piles spacing - s (cm)	126	126	120	567	120	340	120	226	170
Raft area - A_R (m ²)	196	196	64	196	64	64	64	64	64
Piles group area - A_G (m ²)	63.5	14.3	5.8	12.9	13.0	46.2	23.0	46.0	46.2
FF	0.02	0.04	0.05	0.07	0.10	0.13	0.18	0.19	0.26

4. Results and discussion

In this section, the results obtained in the models are presented and discussed. All measurements were converted to prototype values. To carry out a comparative analysis of the settlements of the PRFS, the Filling Factor (FF) presented in Equation 1 was used. The FFs were determined for each model based on the respective geometric conditions, as summarised in Table 7. The models are organised according to the increasing FF, considering that the FF is taken as being nil for a raft without piles.

As mentioned above, the measured displacements, both on the ground and on the raft, were scaled to the equivalent prototype dimensions. For all flight stages, the results obtained at the end of the stage were analysed without consideration to the climb ramp, i.e. the acceleration time of the equipment until the gravitational field was reached.

The settlements measured at the end of each stage, in which the respective model was implemented according to its arrangement (on the soil or on the raft), are averaged and presented in Table 8. These settlements are representative of the long-term behaviour of PRFS.

From Table 8 in general, for Stage 3, the settlement of the soil (E_s) is higher when compared to the settlement of the PRFS (E_r). As a consequence, there may be separation of the raft and the ground, as was indeed verified in the models made at a 200g scale and as illustrated in Figure 7.

The reported settlements were normalised with respect to the thickness of the equivalent raft in the prototype, which represents the stiffness of the raft, in such a way that an adequate parametric analysis can be performed. Figure 8 represents the general trend of the PRFS settlements (measurement over the raft - dr) normalised by the raft thickness (e_R) for the 200g scale models. It can be seen that systems that have piles grouped in the centre of the raft present greater settlement, when compared to those that have piles distributed throughout their area. Chow et al. (2001), Balakumar (2008) and Chung Nguyen et al. (2013) confirmed that there is only a reduction in differential settlements when the piles are concentrated in the central area, since the effects of spacing and pile number influences the overall settlement of the system.

Table 8. Average settlements measured in each model.

Model	Stage 2		Stage 3	
	E_s	E_r	E_s	E_r
m1*	16.1	50.1	61.9	47.2
M3	29.4	34.1	34.1	33.5
M4	25.4	29.3	42.0	37.9
m2	27.2	21.1	71.8	27.8
M6	44.6	47.0	22.8	20.6
m3	31.1	12.3	71.9	21.0
m5	28.3	14.9	68.1	24.0
m4	31.3	7.3	74.8	17.0
m6	28.3	6.5	66.7	19.8
m7	32.3	4.5	62.3	15.2

m1*: raft without piles at 200g scale. M1 has failed and is not included.

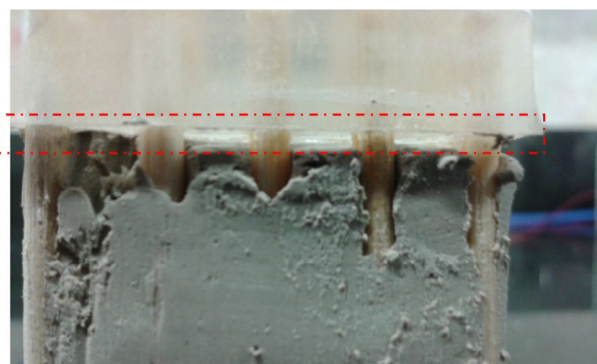


Figure 7. Raft-soil separation on model type m.

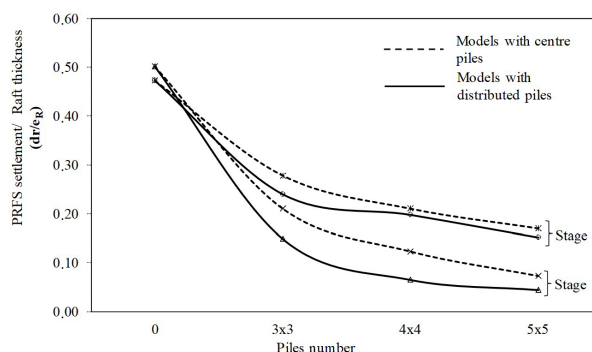


Figure 8. Comparison of PRFS settlement normalised in 200g models.

Figure 9 presents the PRFS settlement values measured over the raft (dr), normalised for all models, allowing the establishment of a trend of settlement behaviour, as a function of the Filling Factor (FF) and the consolidation condition, with and without water extraction. Bajad & Sahu (2008) indicated that when the number of piles increases, the reduction of the settlements of PRFS is greater. In fact, it can be seen that if the number of piles exceeds a certain value, the increase in the efficiency of the PRFS over the reduction of settlements is marginal, as reported by Rodríguez-Rebolledo et al. (2015). Figure 10 shows that the settlements generally decrease while the FF increases, with a certain tendency to stabilise. This may be because, for low separations, the influence of the group effect is increased, decreasing the capacity of the group.

Figure 9 suggests that the efficiency in decreasing settlements is lower for higher values of FF. The trend of the two lines allows us to observe that the percentage of difference in the settlements for the two situations, with and without water extraction, can be up to 20%.

According to Rodríguez-Rebolledo et al. (2015), the difference between the settlement measured over the raft (dr) and the settlement measured on the soil (ds), indicates the effective displacement of the PRFS. When the difference is positive, it can be said that the system settles, otherwise, the system presents emersion. Figure 10 presents the effective displacement evaluated for the prototypes represented by the studied models. From Figure 10 one can observe that the 70g scale models, with FF values less than 0.07, show settlement in the two stages. The 200g scale models mostly present emersions. Emersions are higher in Stage 3 and are influenced by deep water extraction processes and the consequent change in the pore pressure condition; this is confirmed by the separation of the raft, observed in Figure 8. It can also be seen that the relative settlement tends to be stable in Stage 3, showing the greatest influence of the water extraction processes on the behaviour of all the evaluated systems. In this case, the general settlement will depend to a greater extent on the actual settlement of the soil.

Another parameter presented in Equation 3, which allows analysis of the influence of the inclusion of piles in the PRFS, is the settlement reduction ratio (Sr), which is graphically presented in Figure 11.

The reduction of the settlements appears to be greater as the FF increases; high FF values are normally associated with a greater number of piles and greater separations between them. From Figure 11, it should be noted that even when the presence of piles reduces the settlements of the PRFS, the reduction efficiency is lower, when the soil is subjected to the double consolidation process by external loads and extraction of water from deep layers (subsidence). The efficiency of the piles can be up to 29% lower in this case, compared to the conditions of a PRFS subjected only to consolidation by external load.

For higher FF, the piles offer greater resistance to settlement due to the presence of the load. However, when

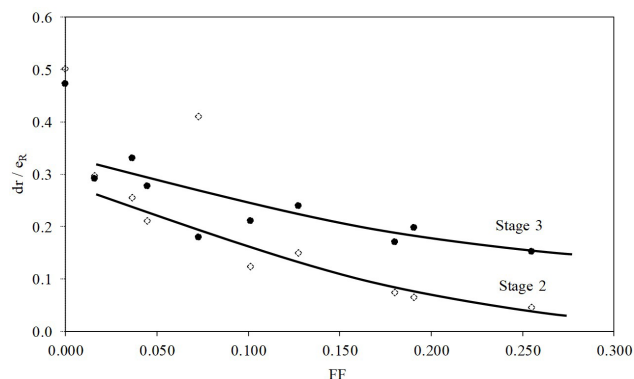


Figure 9. Settlement trend for the PRFS evaluated.

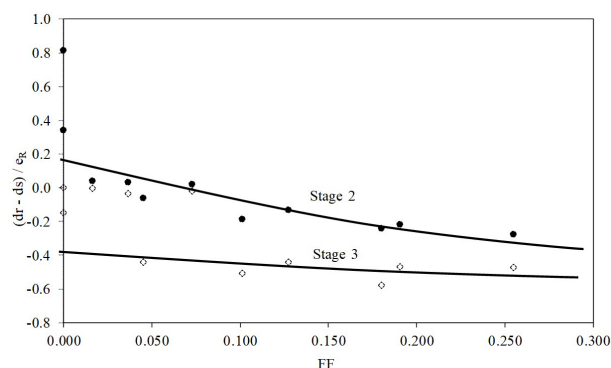


Figure 10. Effective settlement of the PRFS evaluated.

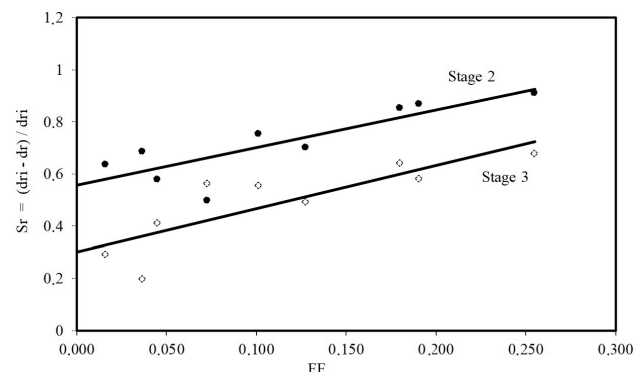


Figure 11. Settlement reduction ratio of the PRFS evaluated.

there is additional abatement to the loading process, the largest settlements are influenced by the general displacement of the soil layer and, thus, the PRFS system sinks together with the soil.

5. Conclusions

In this work, a physical model via geotechnical centrifuge simulating the complex behaviour of a Piled Raft Foundation System (PRFS) founded in soft soils undergoing regional subsidence was developed to understand the induced

settlements by the consolidation process and the double process of consolidation and extraction of water from deep layers.

With the settlement results of this models, it was shown that PRFS that have piles grouped in their central zone present greater settlement when compared to those systems that have piles distributed throughout the entire area of the raft, since the settlements are influenced by both the spacing between the piles and the quantity of piles in the system.

To analysing the settlement response, the Filling Factor (FF) of a PRFS was used. The FF represents the influence of the geometry or geometric distribution over the behaviour of PRFS response. This work shows when the Filling Factor (FF) increases, the reduction in settlement of the PRFS system is greater. However, the percentage at which the piles reduce the settlement decreases, because there must be an optimal number of piles, above which the inclusion of new piles does not have a significant influence on settlement control.

The settlements induced in PRFS founded on soft clays are not necessarily controlled by placing a greater number of piles under the raft or with greater spacing, since, as shown, as the Filling Factor (FF) increases, the effectiveness of the piles decreased.

The reduction in settlements is less when there are additional consolidation processes due to the extraction of water from deep levels, with differences of up to 20% between the condition with and without water extraction.

This work shows that in the subsidence processes represented by the extraction of water from deep soil layers, the settlements of PRFS are greater, mainly because the PRFS system is embedded in a double consolidation process by the loading and reduction of pore pressures. In the reduction of pore pressure process, the greater settlements of the soil, if compared with those of the PRFS system, cause a gradual loss of contact between the soil and the raft, with the consequent possibility of reducing the load capacity of the system.

The results presented can be useful either for future design scenarios or for adjusting analytical methodologies of this same system, since it optimises the performance of this type of foundation structure when undergoing a regional subsidence phenomenon.

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Declaration of interest

The authors wish to confirm that there are no known conflicts of interests associated with this publication and

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Authors' contributions

Edgar Rodríguez Rincón: conceptualization, methodology, investigation, validation, writing - original draft. Bernardo Caicedo Hormaza: supervision, conceptualization, methodology and resources. Juan F. Rodríguez Rebolledo: supervision, conceptualization, methodology.

List of symbols

A_G	Piles group area
A_R	Raft area
B	Width raft
C_c	Compression index
C_s	Swelling index
C_v	Vertical consolidation coefficient
d	Diameter pile
dr	Settlement of PRS
dri	Settlement of raft without piles
ds	Soil displacement
E	Elasticity Modulus
E_s	Settlement measured for the LVDT over the soil
E_r	Settlement measured for the LVDT over the raft of the PRFS
e_R	Raft thickness
FF	Filling factor
g	Gravitational acceleration
G_s	Specific gravity
I_p	Plasticity index
L	Raft Length or pile length
N_p	Piles number in the group
$PRFS$	Piled Raft Foundation System
s	Piles spacing
S_r	Settlements Reduction Ratio
w_L	Liquid limit
w_p	Plasticity limit

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