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Analysis of piled-raft foundation systems (PRFS) founded on soft clay, via geotechnical centrifuge teste

E. Rodríguez Rincón
Muniz e Spada Engenheiros Consultores, Rio de Janeiro, Brazil, edgar@munizspada.com.br

B. Caicedo Hormaza
Universidad de Los Andes, Bogotá, Colombia, bcaicedo@uniandes.edu.co

R. P. da Cunha, J. F. Rodríguez Rebolledo
Universidade de Brasília, Brasilia, Brazil, rpcunha@unb.br, jrodriguezr72@unb.br

ABSTRACT: Piled Raft Foundation Systems (PRFS) are using in soft clays in recent years. In this type of soil, a double consolidation process can occur, due to the load imposed on the foundation and transmitted to the soil, and due the modification of internal stress conditions. This experimental work uses reduced scale models to analyse the behaviour of PRFS subjected to double consolidation processes. The analysis is carried out based on the settlements and the modification of the load distribution over the fart and the piles. The influence of the spacing and number of piles on the PRFS behaviour was verified. The results show that greater spacing between piles in PRFS is more effective for controlling the settlements, when the soil is subjected to subsidence processes and, the modification of the load assumed by the raft is similar to that which had already been proposed in previous investigations.

1 INTRODUCTION

According to Poulos (2001), Piled Raft Foundations Systems (PRFS) are increasingly being used as a foundation element in infrastructures. The capacity of the raft is increasing with the piles' inclusion and the piles controls the total and differential settlements. In general, the inclusion of piles in PRFS can reduce the necessary length of the piles and reduce their number, improving the functionality of the system.

Some cities in Asia and Latin America have implemented the use of PRFS as a foundation system (Banerjee, 2009). The PRFS in these cities have presented damages associated with subsidence processes, because of the extraction of water or loss of aquifer recharge (Bareño and Rodríguez, 1999). In PRFS built under these conditions, failure under extreme conditions can be occur by the negative friction generated over the piles, as a product of induced additional vertical loads and settlements (Leung et al., 2004; Auvinet and Rodríguez, 2017).

Lee et al. (2010) mentioned that several research studies have found that PRFS do not exhibit adequate behaviour in clay soils, mainly due to the possibility of presenting excessive settlement and low loading capacities. In the case of clays, Cunha et al. (2004) and Ayala (2013) showed that PRFS can be used in tropical clays (e.g., the case of Brasília), presenting an adequate response to load and settlement, and reducing the costs of foundations, particularly in small buildings.

With the use of small-scale models, Thaher and Jessberger (1991) presented an experimental model in a geotechnical centrifuge (50 g) to evaluate the effect of the diameter, length, and number of piles placed under a raft supporting an axial load. Horikoshi and Randolph (1996) conducted an experimental study in a geotechnical centrifuge (100 g) where they analysed the effect of the number of piles, the pressure under the raft, the settlements, and the percentage of the load that the piles could support.

Tran et al. (2012) delved into the consequences of subsidence phenomena in the cities of Ho Chi Min, Bangkok, Mexico City, and Shanghai, where the differential settlement of the structures had increased due to changes in the water conditions of the clay soils in these cities (subsidence phenomena).

Rodriguez et al. (2020) presented an analysis of the settlements generated in PRFS built on soft clays, in which the evolution of the settlements for different consolidation conditions was analysed, including their variation over time.

Cui et al. (2010) reported the importance of considering time-dependent behaviour in the analysis of foundations due to the consolidation of soils and the use of numerical methods to assess the effect of time in a PRFS. The authors also highlighted that there have been few works that analysed the time-dependent behaviour in three-dimensional systems, with respect to the soil-structure/pile-raft interaction, because the variation of the pore pressure in the soil is not normally represented. Thus, the stress-strain behaviour of the soil is not linear, even if it is normally idealised as a linear material.

This document presents the results of modelling four PRFS using a geotechnical centrifuge. The models were subjected to consolidation processes induced by external loading (representing the superstructure) and by subsidence (representing the extraction of water from a deep soil layer or pore water pressure drawdown). The soil was manufactured in the laboratory and corresponded to a soil profile, like that of the Bogotá city soil profile.

Different variables were measured in the models, with the help of appropriate instruments for these purposes. An analysis of the responses of the models was performed, depending on the number and distribution of the piles, the load distribution, and the efficiency of the group to control settlements. In addition, the behaviour of the different systems in the two consolidation conditions is presented.

2 MATERIALS AND METHODS

2.1 Geotechnical centrifuge apparatus

Testing facilities using in this research consist of a beam geotechnical centrifuge with the characteristics shown in Table 1 and Figure 1. The equipment is located at the Geotechnical Models Laboratory of Los Andes University, Bogota, Colombia.

Table 1. Characteristics of the beam-type geotechnical centrifuge.

Turning radius (m)	1,90
Model boxes dimensions (cm)	40 x 50 x 60
Gravitational field maximum (g)	200
Maximum model weight (kN)	4,0
Nominal power (HP)	3
Channels for data acquisition	40

2.2 Measured variables and instrumentation

The following measurements were made in the models, with the help of a indicated instrumentation:

- The PRFS settlements, measured with displacement sensors (LVDT)
- Load distribution on the piles, with load cells over some piles.

2.3 Geometry and materials of the PRFS models

To scale the models, the similarity between models and prototypes must be guaranteed based on the flexural modulus, as shown in Equation 1 (Taylor, 1995).

1. Data acquisition panel 2. Beam
3. Water control tank 4. Modelling boxes platform
5. Motor axis 6. Counterweight platform

Figure 1. Beam geotechnical centrifuge of Los Andes University

$$E_m^{mm} I_m^{mm} = E_m^c I_m^c \tag{1}$$

where $I_m = \frac{bt^3}{12}$: moment of inertia, b: base of the element, t : thickness of the element, E_m^{mm} : elastic modulus of the material in the model and E_m^c : elastic modulus of concrete

Since a specific prototype was not adopted, it was sought to guarantee that at least the values of the modulus would be consistent with typical values recommended in the literature. Equation 1 was applied for the raft, as it is the main element subjected to flexural stress; for all other elements the conversion of dimensions is proportional to the scale factor.

Taking Equation 1 into account and considering a unit base width, the dimensions of the raft-type elements were determined from Equation 2.

$$t_p^c = \frac{t_m^{mm} n_l}{\sqrt[3]{\frac{E_m^c}{E_m^{mm}}}} \tag{2}$$

where t_p^c : concrete thickness in the prototype, n_l : scale factor, t_m^{mm}: thickness of the element made from the corresponding material in the model and E_m^c : the elastic modulus of concrete.

Consolidation is linked to the dissipation of pore pressure in the soil. The consolidation degree is described by the dimensionless time factor Tv in the Equation 3

$$T_v = \frac{C_v\, t}{H^2} \quad (3)$$

where: C_v is the coefficient of vertical consolidation, t is the consolidation time and H is the maximum drainage length. For the same degree of compaction, the dimensionless time factors must be equal in both the model and the prototype, Equation 4.

$$\frac{C_{vm}\, t_m}{H_m^2} = \frac{C_{vp}\, t_p}{H_p^2} \quad then \quad t_m = \frac{1}{N^2}\frac{C_{vp}}{C_{vm}} t_p \quad (4)$$

Thus, it can be observed that if the soil used in the model and the prototype is the same and the time scale factor in the compaction is 1: N^2, where the apparent acceleration of two processes related to time is a consequence of the reduced geometric scale of the model.

The flow paths along which the flow travels have a scale factor for length of 1:N, therefore, the drainage time can be evaluated as presented in the Equation 5.

$$t_m = \frac{L_m}{v_m} = \left(\frac{L_p}{v_p}\right)\frac{1}{N\, v_p} = \frac{1}{N^2} t_p \quad (5)$$

Based on Equation 5, the scale factor for time in flow problems is N^2, equal to that evaluated in consolidation processes.

The load capacity of the geotechnical centrifuge and the modelling box dimensions, allowed the determination of the dimensions and a scale factor to be used. A scale factor of 1/70 (70 g) was used in this research to evaluate the behaviour of the models. Figure 2 present the configurations evaluated and Table 2 present the characteristics of the models, comparing the equivalent dimensions of the prototype they represent. An aluminium plate was used to form a raft (1.3 cm thick and 20 x 20 cm in area) and aluminium tubes of 9 mm in diameter and 320 mm in length were used for the piles.

2.4 Soil profile

According to the principles of geotechnical modelling, the model must duplicate the factors that influence the soil's response, i.e., the level of stresses and resistance.

Rincón and Rodríguez (2001) proposed the soil profile selected to represent the behaviour of soft clay soils. The soil corresponds to a clay profile with a strength that is linearly variable with depth, between 10 kPa to 40 kPa, typical of the city of Bogotá DC (Figure 3). Commercial kaolin was used in the soil profile manufacturing.

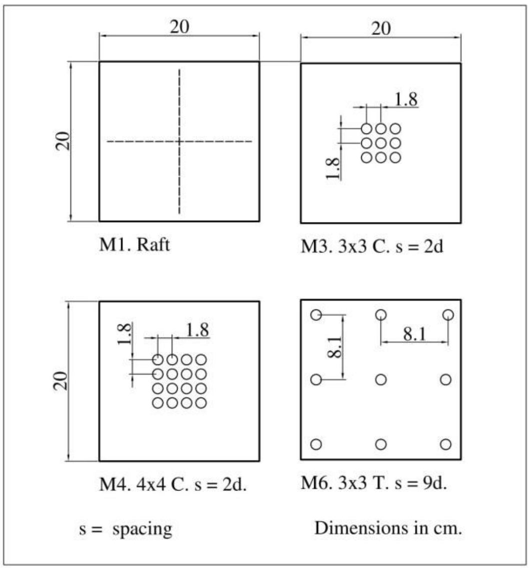


Figure 2. Geometrical configuration of PFRS models

Table 2. Model elements dimensions and prototype equivalences.

Element	Parameter	Model characteristic	Prototype characteristic (equivalent)
Raft	Material	Aluminium	Concrete
	Thickness, e_R	13 mm	1.147 m
	*Elasticity modulus, E	70000 MPa	35000 MPa
	Width, B	200 mm	14 m
	Length, L	200 mm	14 m
Piles	Material	Aluminium	Concrete
	Diameter, D	9 mm	63 cm
	*Elasticity modulus, E	70000 MPa	30000 MPa
	Length, L	320 mm	22,4 m

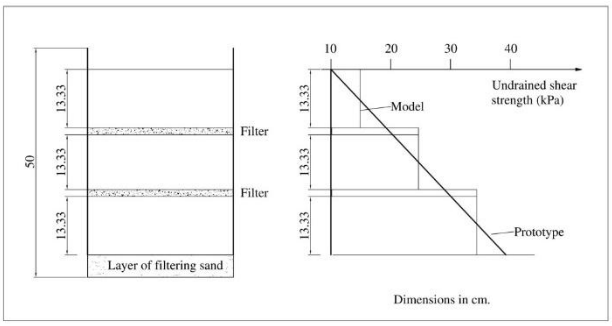


Figure 3. Proposed soil profile

The soil profile is made up of three layers, as shown in Figure 3. To control the linear variation of stress at depth, the undrained shear strength is also measured with the vane shear of the laboratory, at the midpoint of each layer. The procedure proposed by Rincón and Rodríguez (2001) was implemented in this research to the soil fabrication. This procedure is summarised in Figure 4.

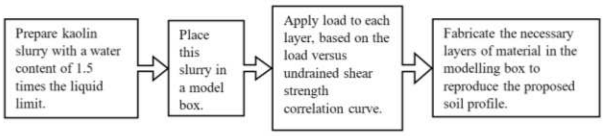


Figure 4. Procedure to soil manufacturing

2.5 Models analysed and instrumentation

The geometric configurations used in this research are presented in Figure 5. A detailed view of the instrument layout is shown in the Figure 6.

2.6 Stages and times on the tests

The current research focused on analysing two working conditions of the PRFS: first, PRFS subjected to external load and, second, PFRS subjected to external loads and subsidence (by water extraction of deep soil layers). In both cases, the analysis was focused on the influence of the consolidation on the response of the foundation system. Three test stages were defined and carried out, as presented in Figure 7.

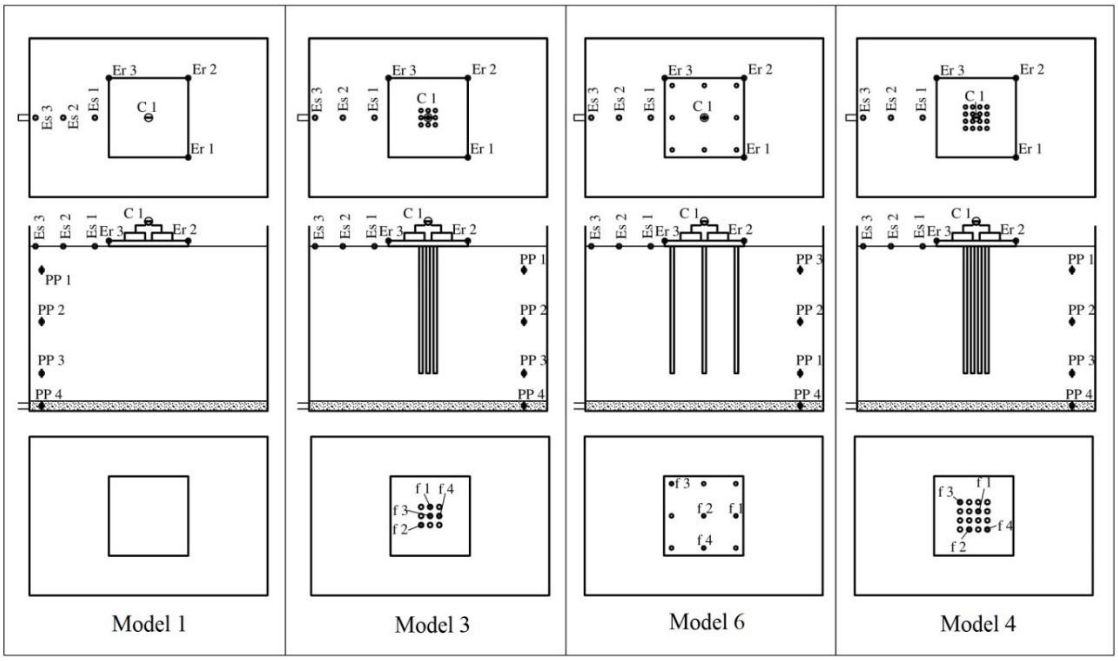


Figure 5. Models and distribution of the instrumentation

The defined test stages and pore pressure conditions are schematised in Figure 5. It is important to mention that it was not possible to make changes to the working conditions in the geotechnical centrifuge during each testing stage of the models. Therefore, flights had to be performed in stages and then stopped when a physical modification to the model had to be made that could not be replaced by an automatic process. The testing with the model included pausing between Stage 2 (consolidation by external load) and Stage 3 (consolidation by external load and subsidence) to allow modifications to be made to the model. This stopping time was short, compared to the test time, and the soil rebound was controlled.

3 RESULTS

3.1 Measured displacements

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 reaching the sought gravitational field (times interval t_C-t_D and t_G-t_H in Figure 7).

In the models, incremental displacements at each stage were measured. These displacements were obtained by closing each instrument and restarting the measurement at each stage, due to the stops between the stages of the test. The incremental displacement profiles are presented in Table 4 for each model.

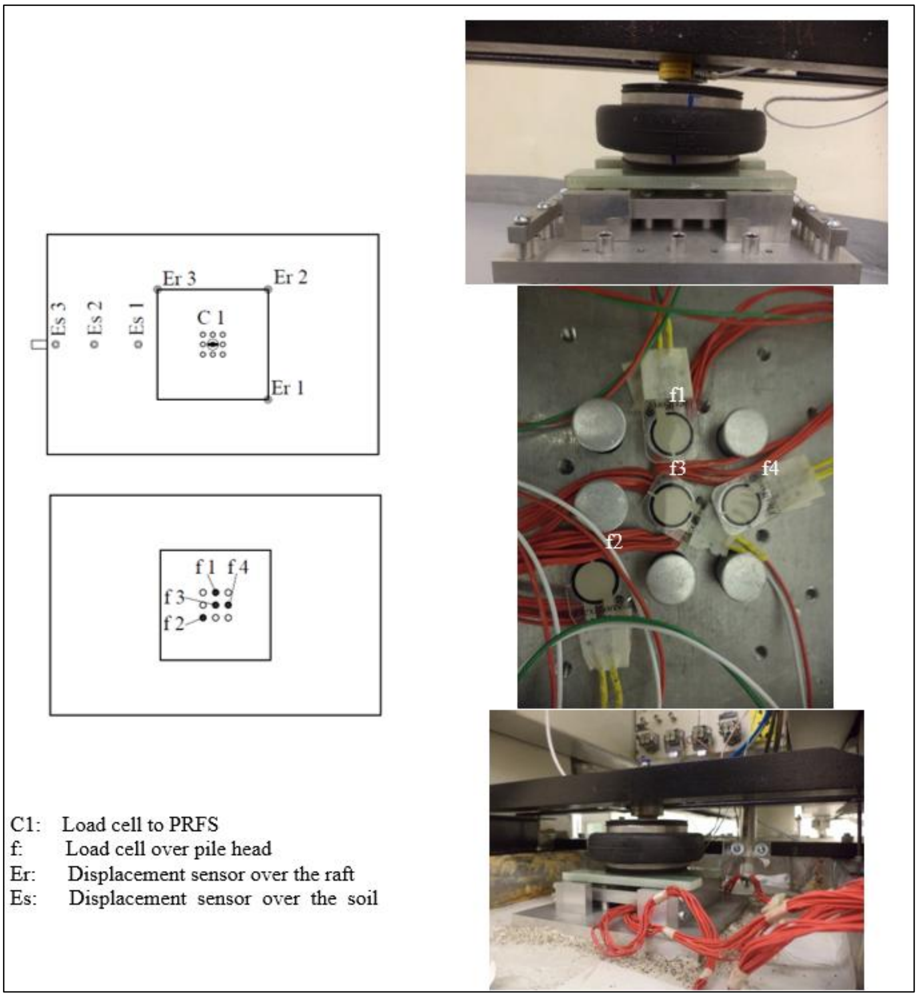


Figure 6. Model assembly details

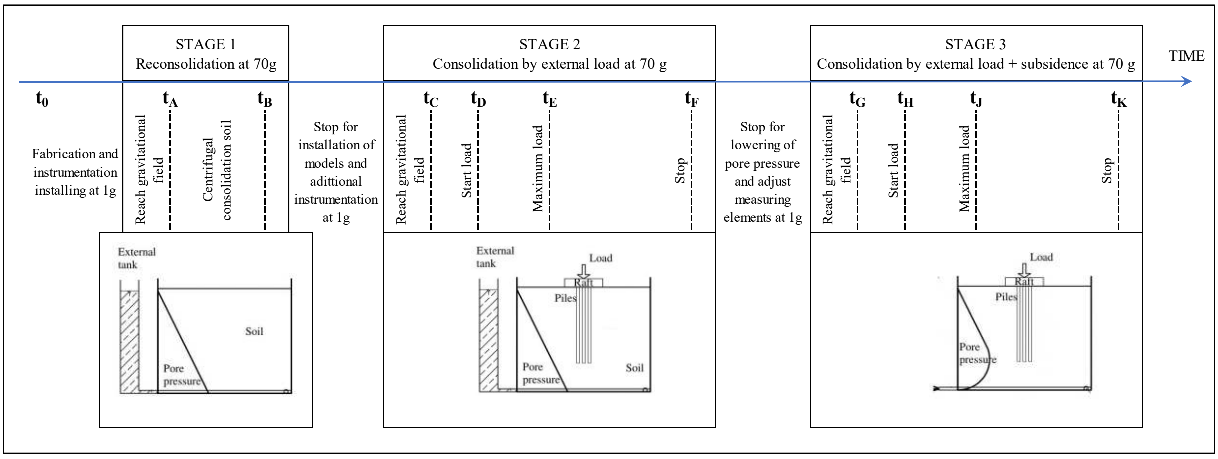


Figure 7. Stages, pore pressure and time line to the models

Table 3. Stages for the test

Activity	Range	Flight time (h:min)
Model soil preparation	t_0 - t_A	
Stage 1	t_A - t_B	1:54
Stop for instrument and model installation	t_B - t_C	
Stage 2	t_C - t_F	2:54
Stop for external water tank disconnection	t_F - t_G	0:30
Stage 3	t_G - t_K	2:54

Table 4. Effective displacements

Model	Stage	Es3	Er	Es3 – Er	Effective displacement (cm)
M3	2	26.4	34.1	-7.7	-10.9
	3	30.3	33.5	-3.2	
M4	2	22.4	29.3	-6.9	-5.2
	3	39.6	37.9	1.7	
M6	2	40.6	47.0	-6.4	-9.7
	3	17.3	20.6	-3.3	

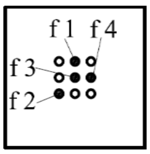
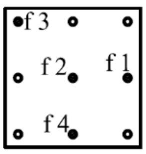
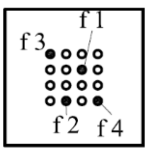
The displacements (and physically) allowed us to observe that the M1 model presented a total failure. For the other models, the general displacement was controlled by the presence of the piles. In the M6 model, larger settlements occurred in Stage 2 due to the loss of water pressure inside the model box.

3.2 Load distribution in the system

One of the objectives of the present investigation was to determine the variation that occurs in the load supported by the piles when water is extracted as part of the process. With the results of the load readings from the cells on the pile heads, it was possible to establish the proportion of the final load that is borne by each pile (see Table 5).

To determine the total load on the piles, it was assumed that piles in symmetrical positions had similar loads. Therefore, by knowing the loads measured by the load cells placed in some piles of the model (Table 5), the load value supported by the group of piles could be determined (Lee, 1993). The proportion of the load in Stage 2, initially assumed by the raft, was between 74 and 77%; this proportion was lower when water extraction occurred, reaching values between 46 and 54%. This variation indicates that there was a load transfer from the raft to the piles.

Table 5. Load distribution in the piles of the PRFS models

Model	Load cell distribution in the model	Location by symmetry of the cells		Stage 2	Stage 3
M3		f2 f1 f2 f4 f3 f4 f2 f1 f2	Total load on the piles (kN)	1753,86	3423,10
			System load reading (kN)	7496,56	7417,85
			Load percentage on the piles	23%	46%
			Load percentage on the raft	77%	54%
		Total piles **9**			
M6		f3 f4 f3 f1 f2 f1 f3 f4 f3	Total load on the piles (kN)	1916,69	3962,80
			System load reading (kN)	7358,82	7319,47
			Load percentage on the piles	26%	54%
			Load percentage on the raft	74%	46%
		Total piles **9**			
M4		f3 f2 f2 f3 f2 f1 f1 f2 f2 f1 f1 f2 f4 f2 f2 f4	Total load on the piles (kN)	1862,61	3504,39
			System load reading (kN)	7417,85	7398,18
			Load percentage on the piles	25%	47%
			Load percentage on the raft	75%	53%
		Total piles **16**			

3.3 Load / displacement analysis

Figures 8 and 9 show the proportion of the load that is supported by the pile group (expressed by the percentage of the total load over the PRFS and the average settlement of the raft, for the different times intervals already defined for Steps 2 and 3, respectively. The proportion of the load value taken by the piles and the total load value in the PRFS (at each interval of time) allowed us to establish the parameter α_p, i.e., the load percentage on piles.

In Figure 8, the load percentage on the piles in the initial stage was higher and then decreased with settlement until it reached a more or less constant value.

For Stage 3 (Figure 9), the proportion of the load supported by the piles in the initial time interval was greater than stage 2, but then decreased rapidly. The final load percentage on piles value supported by the piles was higher in Stage 3 than in Stage 2.

There are no significant differences for greater numbers of piles or spacing, in terms of high settlement values in stage 2. When subsidence by water deep extraction (stage 3) ocurrs, models with greater spacing (M6) present higher values of load distribution factor.

The load percentage on the piles (α_p) depends not only on the geometry of the system, but also on the total applied load (Lee et al., 2010). In fact, this coefficient (which expresses the proportion of the load assumed by the piles) also depends on the condition of the water in the soil, as it can be observed that the values are higher for conditions where water is extracted from the soil (stage 3) than for conditions with load only (stage 2).

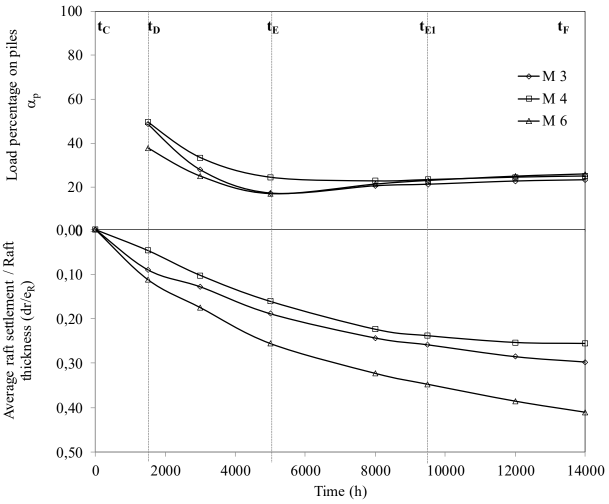


Figure 8. Proportion of load supported by the piles compared with the average settlement in Stage 2

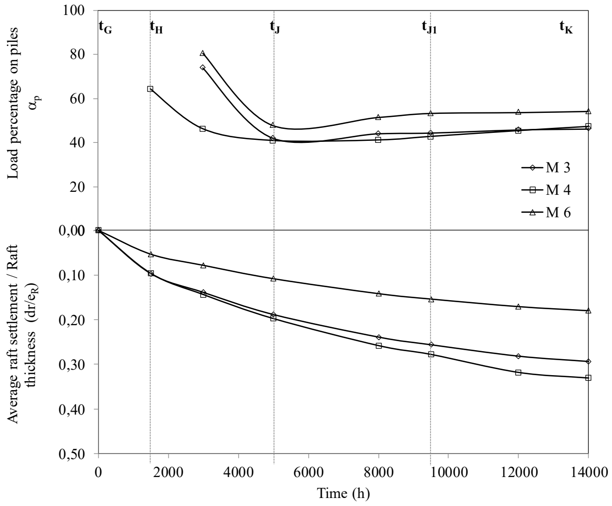


Figure 9. Proportion of load supported by the piles compared with the average settlement in Stage 3

4 CONCLUSIONS

In the present investigation it has been demonstrated that the inclusion of piles in PRFS is effective in controlling the settlements generated in a foundation raft founded over soft clays. However, when PRFS were subjected to a double consolidation process, the subsidence associated with the decrease in pore pressure in deep soil clay layers resulted in greater soil settlement. This settlement was not necessarily accompanied by the elements of the PRFS, bringing consequently a possible separation of the raft and the soil and, a greater load on the piles.

The proportion of the load being supported by the piles increased when water was extracted. In fact, the proportion of the load assumed by the piles grew rapidly in the first stages of loading and remained constant if the loading conditions were not modified.

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REFERENCES

Auvinet, GY, Rodríguez Rebolledo, JF. (2017) "Criteria for the design of friction piles subjected to negative skin friction and transient loads", *Ingeniería Investigación y Tecnología*, **18**(3), 279-292. https://doi.org/10.22201/fi.25940732e.2017.18n3.025

Ayala, DJ. (2013) “Use of Piled Raft Foundation for small buildings founded on collapsible soil” (In Portuguese), M. Sc. Thesis, Post-graduate Program in Geotechnics, University of Brasilia, Brasília D.F.

Banerjee, S. (2009) “Centrifuge and Numerical Modelling of Soft Clay-Pile-Raft Foundations Subjected to Seismic Shaking”, Ph. D. Thesis, Department of Civil Engineering, National University of Singapore.

Bareño, EE, Rodriguez, E. (1999) “Clays Shrinkage” (In Spanish), Undergraduate Thesis, Department of Civil and Agricultural Engineering, National University of Colombia.

Cui, C, Luan, M, Li, M. (2010) “A study on time-effects of pile draft system by using computational methods”, *GeoShanghai 2010 International Conference,* Geotechnical Special Publication, 42-51. https://doi.org/10.1061/41106(379)4

Horikoshi, K, Randolph, MF. (1996). “Centrifuge modelling of piled raft foundations on clay”, *Géotechnique*, **46**(4), 741-752. https://doi.org/10.1680/geot.1996.46.4.741

Lee, CY. (1993). “Pile groups under negative skin friction”, *Journal of Geotechnical Engineering*, **119**(10), 1587-1600. https://doi.org/10.1061/(ASCE)0733-9410(1993)119:10(1587)

Lee, J, Kim, Y, Jeong, S. (2010). “Three-dimensional analysis of bearing behavior of piled raft on soft clay”, *Computers and Geotechnics*, **37**(1), 103-114. https://doi.org/10.1016/j.compgeo.2009.07.009

Leung, C, Liao, B, Chow, Y, Shen, R, Kog, Y. (2004). “Behavior of pile subject to negative skin friction and axial load”, *Soils and Foundations*, **44**(6), 17-26. https://doi.org/10.3208/sandf.44.6_17

Poulos, HG. (2001). “Piled raft foundations: design and applications”, *Géotechnique*, **51**(2), 95-113. https://doi.org/10.1680/geot.2001.51.2.95

Rincón, CL, and Rodríguez, E. (2001). “Centrifuge physical modelling of a wall without anchors in a soft clay” (In Spanish), M. Sc. Thesis, Department of Civil and Environmental Engineering, Los Andes University.

Rodríguez, E, Cunha, R, Caicedo, B. (2020). “Analysis of settlements in piled raft systems founded in soft soil under consolidation process”, *Canadian Geotechnical Journal*, **57**, 537-548. https://doi.org/10.1139/cgj-2018-0702

Taylor, RN. (1995). “Centrifuges in modelling: principles and scale effects”. In: Geotechnical centrifuge technology. Edited by R.N. Taylor. Blackie Academic & Professional, London, 20 – 34.

Thaher, M, Jessberger, HL. (1991). “The behavior of pile-raft foundatios, investigated in centrifuge model tests”, *In: Centrifuge 91: proceedings of the International Conference Centrifuge 1991*, Boulder, Colo., 13 - 14 June 1991.ISMFE, 225-234.

Tran, TV, Teramoto, S, Kimura, M, Boonyatee, T, Vinh, LB. (2012). “Effect of ground subsidence on load sharing and settlement of raft and piled raft foundations”, *World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, **6**(2), 120-127.