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Comparison of Numerical Methods for Piled Raft Foundations

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Abstract. The methodologies used to calculate piled raft foundations are normally more complex than conventional foundations due to the large number of variables involved in the problem. In the conventional block, the interaction variables considered are only between the pile and the soil. In the piled raft, all the interaction effects must be considered, as follows: plate-soil, plate-piles and piles-soil, simultaneously. The Finite Element Method (FEM) has proven to be a useful tool in analyzing these types of problems. This study aims at assessing the behavior of piled rafts using the Cesar-LCPC numerical tool, version 4.0, which is based on the finite element method. Literature cases of rafts supported by 9, 15 and 16 piles were analyzed. The results obtained were compared with analysis methods presented in the bibliography. The following parameters were assessed: relative spacing (S/D), relative length (L/D), relative stiffness between piles and the soil (K_{PS}), and settlement of piles and the raft. The spacing between piles has a significant influence on load distribution between piles and the raft. Very small spacing provides stiffness to the foundation, which then functions as a conventional pile foundation, in which only the piles absorb the load from the superstructure. The larger the L/D ratio, the lower the settlement and for a given modulus of elasticity of the pile, the increase in relative stiffness (K_{PS}) causes an increase in settlement. In all analyses, the data obtained corroborated the results presented by other methods published in the literature.

Introduction

Tall buildings have been used in large urban centers to compensate for the scarcity of construction areas. These structures impose high loads on the soil. The conventional solutions for transferring loads to the subsoil consist of direct raft foundations, which distribute the load of various columns over a large area, thereby decreasing the stress applied to the soil, or groups of piles that transfer loads to great depths can also be used. Rafts may result in the occurrence of settlements that can compromise the functioning of the structure. The use of piles is technically feasible, albeit costly. A solution to the problem of foundations for tall buildings has been the piled raft, owing to its lower cost, shorter execution time and better performance, both in terms of load capacity and reduced settlements [1;2]. [3] report that the term “block of piles” refers to the classic foundation, in which only the piles absorb and transfer to the soil all the load applied to the foundations, whereas the only structural role of the block is to interconnect the piles. The piled raft is similar to the group of piles interconnected by a block, with the basic difference of considering contact of the block with the surface soil, and consequently its contribution to load capacity and stiffness.

[4] state that the term piled raft is described in articles as a foundation system in which the piles and the raft interact with one another and with the adjacent soil to sustain vertical and horizontal loads and bending moments originating in the superstructure.

The methodologies used to calculate piled raft are normally more complex, since there is a need to consider the interaction between the raft and the soil, the piles and the raft and the piles and soil simultaneously. Studies on piled raft foundations and the influence of geometric parameters and system stiffness on foundation behavior were conducted by [5, 6, 7, 8, 9].

There are a number of methods that seek to predict piled raft behavior. These range from simple methods based on empirical correlations [10, 11, 12, 13]), equivalent foundation methods [14,15] and methods based on the theory of elasticity [15,16, 17, 18], among others, to more sophisticated methods, such as the Boundary Element Method (BEM) and primarily the Finite Element Method (FEM). This study applies the FEM, which is contained in Cesar-LCPC software, in order to assess the behavior of four piled raft cases published in the literature with the aim of comparing the results obtained with Cesar-LCPC predictions.

Cases Analyzed

Raft supported by 9 Square Piles and Centrally Loaded Column

The case was proposed by [19] and analyzed by [18], [20] and [21]. It involves a raft supported by 9 square piles in homogeneous soil, loaded by a central column. Table 1 presents the geometric and elastic parameters used in numerical analyses.

Table 1: Geometric and elastic parameters used to analyze the case of a raft supported by 9 square piles.

D [m]	**A_P [m^2]**	**B [m]**		**L [m]**
1.0	1.0	3.L		17.0 and 37.0
H/L	**E_P [GPa]**	**ν_c**	**ν_s**	**t [m]**
1.5	20.0	0.20	0.45	3.0

D –Side of the pile section; **A** – Cross-sectional area of the pile; **B** – Horizontal Domain; **L** – Pile length; **H/L** – Vertical Domain; **Ep** – Modulus of Elasticity of Concrete; **ν_c** – Poisson's ratio of concrete; **ν_s** – Poisson's ratio of soil ; **t** – Raft thickness;

The modulus of elasticity of concrete was fixed at 20GPa, while the modulus of elasticity of soil ranged from 80MPa to 10MPa, which corresponds to K_{PS} values ($K_{PS}=E_P/E_S$) between 250 and 2000. Five levels of loading located at the top and center of the raft was applied. Adimensional constants of the settlement that were correlated to the respective constants of pile stiffness/soil (K_{PS}) were established for each analysis condition and based on the settlements.

Rafts supported by 9 and 15 Piles – [22]

This case was proposed by [22], and involves analysis of a raft that receives a load of 9 columns, 6 with load P_1 and 3 with load P_2, which corresponds to double the value of P_1, as shown in Figure 1. Analyses were conducted with the raft supported by 9 and 15 piles.

The case was analyzed in 3 steps (Table 2), in which the total load applied, the safety factor and number of piles were varied. The raft measures 60m² (10m x 6m), with stress rupture of 0.30 MPa, resulting in a load of 18MN. The tensile load and pile compression capacities are 0.786MN and 0.873MN respectively. After safety factors were applied (Table 2), the admissible load in Cases A and C obtained was 12MN and in case B the admissible load was 15MN, distributed over 9 piles.

Table 3 shows the parameters used in analyses. The results and settlement values were compared with traditional methods, such as those proposed by [15], [23], Garp 6 [24] and Garp8, Gasp [25], [26] and [27].

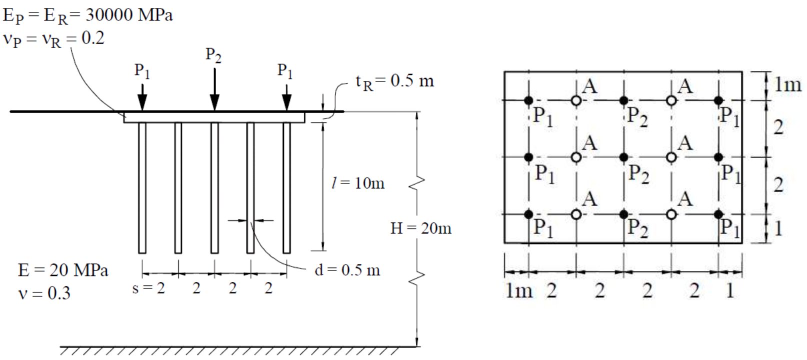

Figure 1 – Example proposed by [22].

Table 2: Loads and safety factors applied in the 3 cases studied.

Step	Nº of Piles	FS	Load on P_1 columns [MN]	Load on P_2 columns [MN]
A	15	2.60	1.00	2.00
B	15	2.07	1.25	2.50
C	9*	2.15	1.00	2.50

* In this analysis the piles marked as A in Figure 1 are disregarded in the foundation.

Table 3: Parameters used in analyses of the case of a raft supported by 9 and 15 piles under varied loads and safety factors.

D [m]	A_P [m²]	B [m]		L [m]
0.5	0.196	3.L		10.0
H/L	**$E_P = E_R$ [GPa]**	**ν_c**	**ν_s**	**t [m]**
2.0	30.0	0.2	0.3	0.5

D –Diameter of the pile section; **A** – Cross-sectional area of the pile; **B** – Horizontal Domain; **L** – Pile length; **H/L** – Vertical Domain; **Ep** – Modulus of Elasticity of Concrete; **ν_c** – Poisson's ratio of concrete, **ν_s** – Poisson's ratio of soil ; **t** – Raft thickness;

Raft supported by 15 piles – [28]

This involves a stiff raft supported by 15 piles on homogeneous soil, which [28] initially modeled by boundary elements. In this analysis, the soil was considered elastic and the distance of the axis from the peripheral piles to the edge of the block corresponds to the pile diameter. The load applied was uniformly distributed over the entire surface of the raft.

In these analyses for a same loading level, the diameter was fixed, and the effect of L/D and S/D ratios of the piles on settlements and load distribution for the raft and piles was analyzed. Table 4 shows the parameters used in modeling.

Table 4: Parameters used in analyses of the case of a raft supported by 15 piles proposed by [26].

D [m]	A_P [m²]	B [m]				L/D		
1.0	0.785	3.L		25	50	100	150	200
H/L	**K_{PS}**	**ν_c**	**ν_s**	**t [m]**			**S/D**	
2.0	1000	0.20	0.49	2.0		3	5	10

D - Diameter of the pile section; **A** – Cross-sectional area of the pile; **B** – Horizontal Domain; **L/D** – Ratio between pile length and its diameter; **H/L** – Vertical Domain; **Kps**- Coefficient of Stiffness between the pile and soil; **ν_c** – Poisson's ratio of concrete, **ν_s** – Poisson's ratio of soil; **t** – Raft thickness; **S/D:** Relative spacing between piles.

Raft supported by 16 Piles – [1]

The TC-18 committee [1] proposes the case of a raft requested for a load of 80MN distributed over its surface, supported by 16 piles in soil that exhibits a modulus of elasticity and increasing undrained resistance with depth, obeying the ratios presented in Eq. 1 and 2. Table 5 exhibits the parameters used in this analysis.

$$Es = 2.45z + 7.0 \text{ (MPa)} \quad \text{Eq. 1}$$

$$Cu = 3.95z + 110 \text{ (kPa)} \quad \text{Eq. 2}$$

Table 5: Parameters used in analyses of the case proposed by TC-18, [1].

ϕ_p (m)	A_P (m²)	B (m)		L (m)	
1.0	0.785	3.L		30	
H/L	$E_P = E_R$ (GPa)	ν_c	ν_s	150	200
				t (m)	S/D
2.0	35.0	0.16	0.1	2.0	3.0

ϕ_p - Diameter of the pile section; **A** – Cross-sectional area of the pile; **B** – Horizontal Domain; **L** – Pile length; **H/L** – Vertical Domain; **E_P**- Modulus of Elasticity of the pile; **E_R** –Modulus of Elasticity of the raft; **ν_s** – Poisson's ratio of soil ; **t** – Raft thickness; **S/D:** Relative spacing between piles.

Presentation and Discussion of the Results

Raft supported by 9 Square Piles and Centrally Loaded Column

Figures 2 and 3 show the results of analyses using Cesar-LCPC software and those of the same analyses conducted by [19], [18] with the ALLFINE software, [20] using the FLEXPDE program and [21], obtained with the DIANA program.

For analyses carried out with 17-meter piles (Figure 2), good agreement was observed between the results obtained here and those presented by the aforementioned authors. In analyses of 37-meter piles, the results put forth by [19] exhibited a relative discrepancy with those reported by other authors and those obtained from Cesar-LCPC.

Figures 2 and 3 show that for a determinate value of deformation modulus of the pile (E_p), the settlement increases with relative stiffness ($K_{PS} = E_p/E_s$), that is, settlement increases with a decrease in E_s.

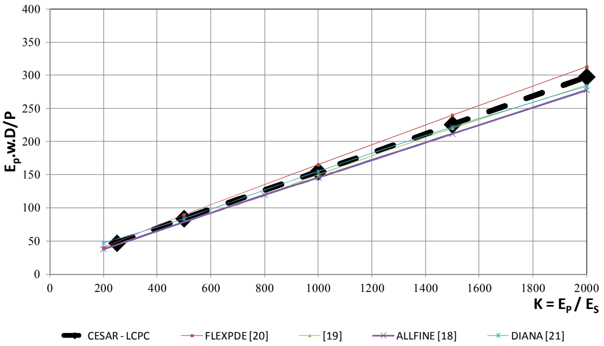

Figure 2 – Results obtained for a raft supported by 9 square piles measuring 17 meters long - Case proposed by [19].

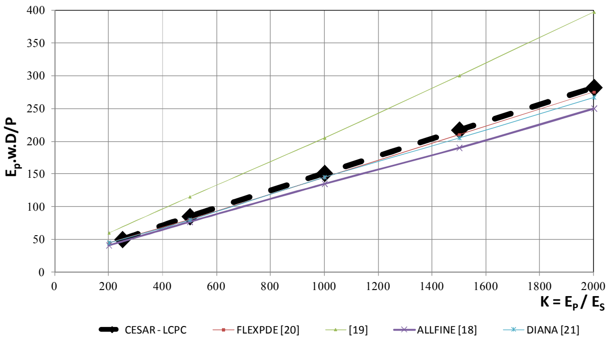

Figure 3 – Results obtained for a raft supported by 9 square piles measuring 34 meters long - Case proposed by [19].

Rafts supported by 9 and 15 Piles – [22]

The results obtained in these analyses are presented in Figures 4, 5 and 6, along with literature results for modeling of the same problem.

Figure 4, where Case A results are illustrated, in which an admissible load of 12MN for a raft supported by 15 piles and safety factor of 2.60 was observed, shows that the settlements obtained ranged between 20.5 and 34 mm, with a mean value of 25.3 mm. The settlement obtained with Cesar-LCPC was 24.3mm, which represents a difference of around 4% from the mean results contained in the literature.

Figure 5 exhibits the settlement values for the condition under which the safety factor considered was reduced to 2.07, and admissible load of 15MN (Case B). In this case, there was a variation in settlements from 26.5 to 44 mm, with a mean value of 33.2 mm. The predicted settlement using Cesar-LCPC was 31.1 mm, differing by 6.3% from the mean value of other methods.

Figure 6 shows settlement values for the condition involving 9 piles (Case C). The safety factor considered was 2.15 and the admissible load, as in Case A, was 12MN. The maximum, minimum and mean settlements obtained by a number of authors were 20.5 mm, 38 mm and 30 mm respectively. The value obtained by Cesar-LCPC was 28.4 mm, only 5.3% below the mean.

Figures 4 to 6 show that the settlements obtained by Cesar-LCPC are compatible with those contained in the literature. Thus, the software used predicts, with the same degree of confidence as others published in scientific journals, the behavior of piled rafts in relation to settlements.

A comparison between Case A (Figure 4) and Case B (Figure 5) shows that a decrease in the safety factor (increasing applied load, with the same number of piles), as expected, led to an increase in settlement value of approximately 22%. A comparison between Case A and Case C demonstrates that removing 6 piles from the base of the raft increased settlement values by an average of 15.6%.

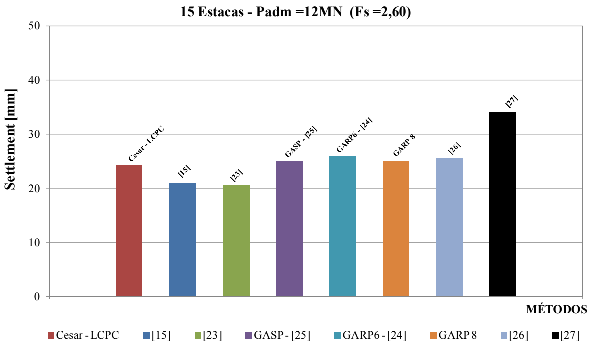

Figure 4 – Mean settlement values in the raft supported by 15 piles and FS of 2.60 obtained in the literature and by the finite element method (Cesar-LCPC).

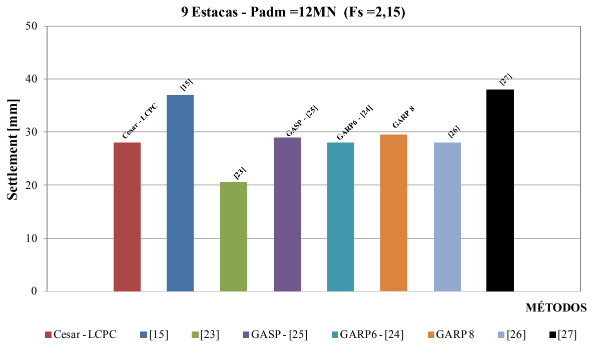

Figure 5 – Mean settlement values in the raft supported by 15 piles and FS of 2.07 obtained in the literature and by the finite element method (Cesar-LCPC).

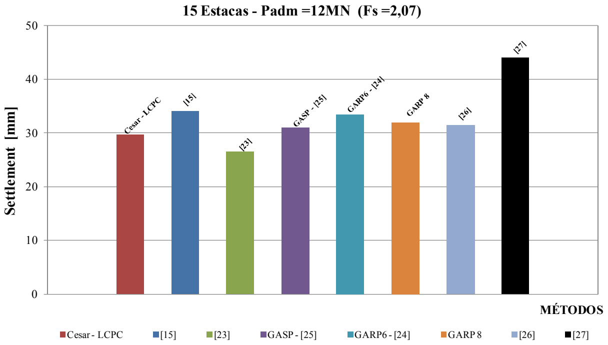

Figure 6 – Mean settlement values in the raft supported by 15 piles and FS of 2.07 obtained in the literature and by the finite element method (Cesar-LCPC).

Raft supported by 15 piles – [28]

Figures 7, 8 and 9 present the results of analyses, as well as the set of findings observed in the literature for modeling of the problem proposed by [28]. According to the results obtained, irrespective of spacing between piles, there was a tendency to agreement with the findings of [21]. The remaining estimated settlement values were slightly higher than those provided by Cesar-LCPC and by [21]. It is important to underscore that the settlement constant used in Figures 7 to 9 is quite sensitive, such that, just a few millimeters of settlement corresponds to a significant variation of this constant. Thus, possible discrepancies exhibited by these methods do not necessarily correspond to significant variations in settlement values.

Figures 7 to 9 show that settlements decrease with an increase in the L/D ratio, up to a value of 100, after which settlement values tended to stabilize. With respect to load distribution between the piles and the raft, the piles with the highest load were those located in the corner and the pile with the lowest load was in the center. For the raft in which the relative spacing between piles was 3, the piles absorbed 97% of the loading applied. For the raft with relative spacing between piles of 5, the percentage of the load absorbed by the piles was 86 % and finally with a relative spacing of 10, the percentage absorbed was 68%.

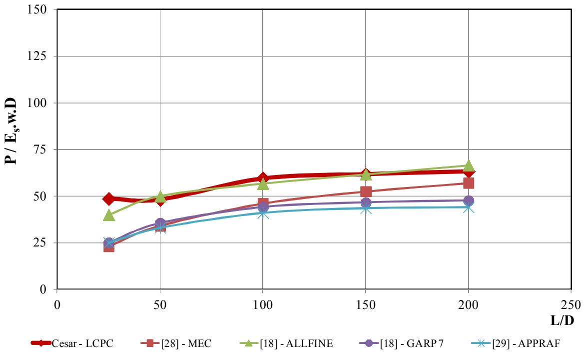

Figure 7 – Results obtained for the raft supported by 15 piles for the S/D ratio of 3.

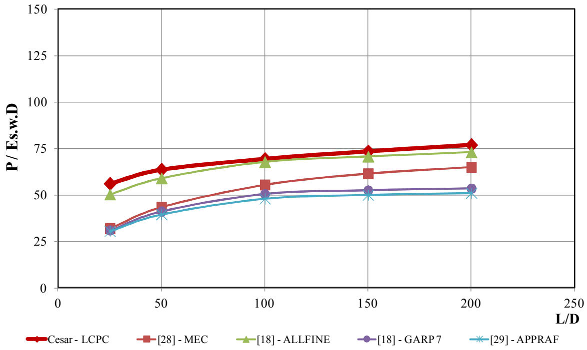

Figure 8 – Results obtained for the raft supported by 15 piles for the S/D ratio of 5.

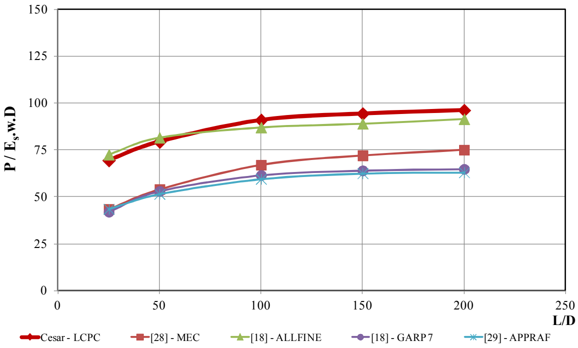

Figure 9 – Results obtained for the raft supported by 15 piles for the S/D ratio of 10.

Raft supported by 16 piles [1]

Table 6 shows settlement values and the load percentage on piles obtained for the case proposed by TC-18 committee. The values obtained in the literature and using the Cesar-LCPC are also illustrated. Once again there is good agreement among the methods used in analyses, especially among those using the FEM.

Table 6: Result obtained in comparison with those observed in the literature for the case proposed by TC-18 ISSMGE. - Modified by [18]

Program / Method / Author	Settlement [mm]	Load on the piles [%]
FEM – [30]	29.0	98.0
Equivalent Pier – [31]	31.0	-
HyPR – [31]	41.0-43.0	100.0
KURP – [32]	42.0	96.0
Garp – Approximate Method	42.0	98.0
PIRAF – Finite Layer Method	31.0	98.0
ALLFINE – FEM – [18]	27.0	95.0
DIANA – FEM – [21]	31.0	-
CESAR-LCPC- FEM	**28.8**	**94.0**

The maximum settlement in the raft was 28.8mm, a value that tends toward the mean results obtained by FEM. It was observed that the piles absorbed 94% of loading and the raft only 6%. This behavior may be due to the small spacing between piles, which results in elevated stiffness in the foundation and consequently does not transfer load through the raft.

Conclusion

Based on the analyses conducted, it was possible to conclude that the Cesar-LCPC software provides results that are compatible with numerical tools used in the study of piled rafts, primarily those based on the FEM.

Numerical modeling of the behavior of three cases of piled raft foundations contained in the literature showed the following: i) settlements increased with a decrease in modulus of elasticity of the soil; ii) settlements increased with an increase in loading on the block and, for a given load, settlement increased with a lower number of piles; iii) spacing between piles had a significant effect on load distribution between the piles and the raft, and the larger the spacing the larger the load borne by the raft and iv) for a relative S/D spacing of 3, the foundation acts as a group of piles, bearing between 94 and 98% of the total load.

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