N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190084

# Numerical Analysis of Piled Raft Composed by Short Piles

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**Abstract.** Geotechnical engineering has often been challenged, requiring technical and economically innovating buildings designs. The architectural concept of these buildings has resulted in the increase and concentration of the loads coming from the structural system. New models of bearing capacity and settlements control have been evaluated to optimize the designs. In this sense, the piled rafts, they come to admit the contribution of the contact of the soil, conceptually denominated piled raft. In this way, the aim of this article is to analyze numerically the behavior of two piled rafts, simulated from sets of rafts composed of two and four piles, spaced five times the diameter. The foundations systems were simulated by means of piled rafts and the three-dimensional (3D) finite element analyzes with the LCPC-Cesar software. The loading was applied to the top of the foundation system and subsequently the load on the top and tip of the piles, as well as, to evaluate the load transfer mechanism, and the contribution of each element (pile and raft). The constitutive model used was Mohr-Coulomb, which takes into account the elastoplastic behavior of the soil. The results showed the contribution of 36 % due to the raft contact and 64 % due to the pile. The numerical analyzes of pile groups, compared to piled rafts, has shown that the greater contribution of the tip resistance is due to the presence of the contact effect.

**Keywords.** Contact, raft-soil, pile group, piles.

## 1. Introduction

Geotechnical engineering has studied new ways to improve the load capacity and settlements control, in order to optimize the conventional design of foundations. In this sense, piled foundations, then came to the contribution of contact of the soil block, conceptually called piled raft. According to Mandolini et al. [1] the concept of piled raft is one that supposes that the piles cooperate with raft instead of being considered as an alternative to this element of shallow foundation.

Physically, a group of piles or block of piles, which is a traditional form of foundation, can be considered to be a piled raft when the block, connected between the piles, is in contact with the soil, thus making the surface element of the foundation [2].

The use of the piled raft technique becomes interesting as a solution for geotechnical designs, as it initially provides an increase in the load capacity of the system, reduction

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of the length of the piles in relation to the conventional design in piled block and standardization of the settlements.

### *1.1. Piled Raft*

The piled raft can be characterized as a function of the result of the load distribution between the elements, piles and raft, using a coeficeinte, $\alpha_{pr}$, proposed by Mandolini [3]:

$$\alpha_{pr} = \frac{\sum_{i=1}^{n} Q_{pile,i}}{Q_{PR}} \tag{1}$$

where $Q_{PR}$ is the total load applied to the piled raft, $Q_{pile,i}$ is the load absorbed by the piles and $\alpha_{pr}$=0 represents a shallow foundation without piles; $\alpha_{pr}$=1 represents a group of piles, in which the top has no contact with the soil. For $0<\alpha_{pr}< 1$, the system works as piled raft (Figure 1).

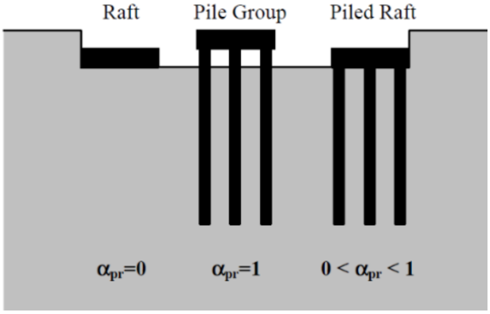


**Figure 1.** Foundation system [3].

### *1.2. Contact effect*

A piled foundation has its load vs. settlement behavior influenced by the presence of a surface element associated with a pile. Poulos [4] considered the pile / block interaction for an isolated pile under a raft in contact with the soil. The author considered the soil to be an elastic semispace and the raft in contact with the soil, crowning the piles as a rigid element. Named by "*L*" the length of the pile, "*d*" the diameter of the pile and "$d_c$" the diameter of the circular raft in contact with the soil. The authors concluded that the lower length of the pile in relation to its diameter (*L*/*d*), greater is the influence of the contact in the reduction of settlements (Figure 2). He also observed that for short piles ($L/d$ <10) the existence of the contact should not be neglected.

The load capacity of the piled raft is not only the algebric sum of the individual capacities of each element of the set, but may be larger, due to the interaction between the parts; and the characteristics of the tested set and the soil type, the contribution of the raft to the load capacity can vary [5]. This same author studied in sand reduced models the behavior of the shallow foundation, the isolated and group of piles with the contact, in order to obtain the contribution of the raft / piles interaction. The author concluded that the load capacity of the piled raft was greater than the algebric sum of the load capacity of the isolated shallow foundation and the group of piles, ie, there is an interrelation between the shallow foundation and the deep foundation when using the system, according to Eq. (2):

$$Q_t = \alpha Q_g + \beta Q_c \tag{2}$$

where $Q_t$ is the load capacity of piled raft; $Q_g$ is the load capacity of pile group; $Q_c$ is the load capacity of isolate pile; $\alpha$ is the increase factor of the group load capacity due to the interaction; $\beta$ is the increase factor of the shallow foundation due to the presence of the group of piles.

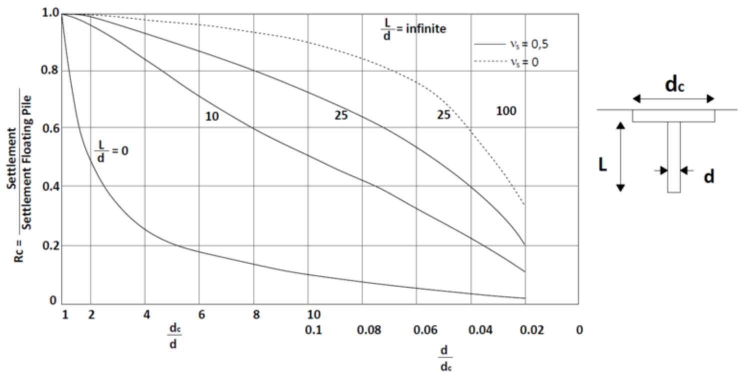


**Figure 2.** Contact effect of isolate pile [4].

## 2. Material and methods

The piled rafts were executed with two and four piles and dimensioned structurally with the software CYPECAD (version 2015.n), as rigid elements with angle of inclination of the compression rod ($\theta$), between 40 ° and 55 °. The geometry of the piles was 5 m in length and 0.25 m in diameter. The spacing ($s$) adopted between the piles was five times its diameter (5 $\phi$) and covering ($c$) of the axis until the face of the raft, in such a way that it could guarantee a greater area of contact of the raft with the soil and behavior close to the piled raft (Figure 3).

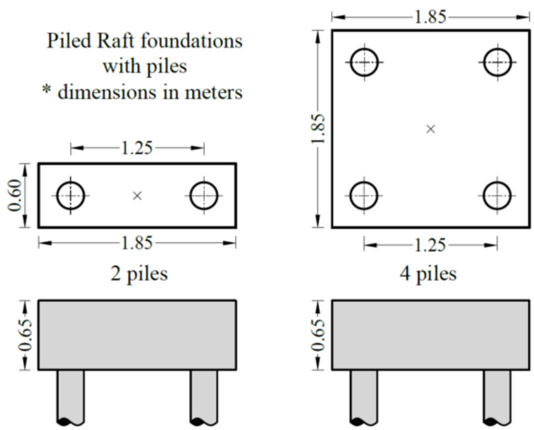


**Figure 3.** Plan view and elevation details of piled rafts foundations.

In this paper, the numerical modeling was performed on a quarter of the problem due to the symmetry along the axis of the piles and raft, resulting in a rectangular 25m×25m section block and 10.8 m in depth (Figure 4).

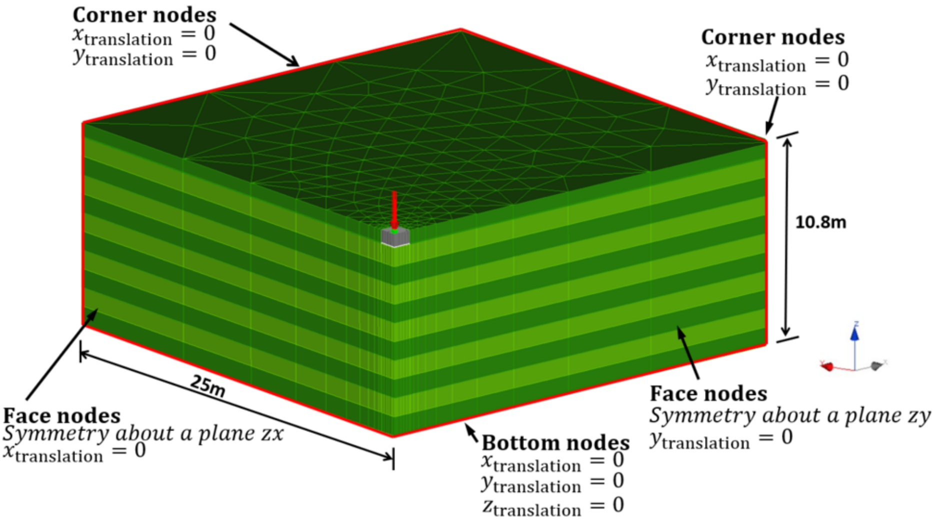


**Figure 4.** Model of finite elements.

These dimensions were attributed after testing performed to make sure that the boundary conditions assigned at the ends of the model could be considered no displaceable or else had very low displacements and, therefore, could not affect the results of the analyses. The elastoplastic model used varied according to the stresses applied, following a non-linear stress *vs* strain behavior. The mesh of finite elements included quadratic interpolation triangular shaped elements, which were extruded every meter in depth.

The soil properties of the different layers followed Mohr-Coulomb criterion. For materials with fragile behavior (concrete), the parabolic model was used. The CESAR v.5 software program (manufactured by Itech-soft) was used for numerical analyses. The parameters used in analyses for soil and concrete are shown in Table 1. These were adopted for a qualitative evaluation, with no intent of analyzing a specific case.

**Table 1.** Strength and strain parameters of soil and concrete.

| **Material** | **E** [kPa] | **γ** [kN/m³] | **$R_c$** [kN/m²] | **$R_t$** [kN/m²] | **c'** [kN/m²] | **ϕ'** [°] | **ν** [-] |
|---|---|---|---|---|---|---|---|
| Soil | 16 | 16 | - | - | 20 | 25 | 0.33 |
| Concrete | 25,000 | 25 | 25 | 2.5 | - | - | 0.20 |

E: Young's modulus; γ:unit weight; c': cohesion; ϕ': friction angle; ν: Poisson's ratio; $R_c$: compression strength; $R_t$: tensile strength.

## 3. Results and discussions

From the data obtained by means of numerical modeling, it was possible to get the load *vs*. settlement curve for the piled rafts. For the two piles, the ultimate load was 405 kN and 46.71 mm of displacement. The conventional load for a displacement of 10% of the nominal diameter of the pile (25 mm) resulted in 351 kN and consequently in a allowable load of 175 kN with 1.64 mm displacement. In the case of the piled raft with four piles, the ultimate load was 700 kN and 38.38 mm displacement. The conventional load for a displacement of 10% of the nominal pile diameter (25 mm) resulted in 646 kN and, consequently, the allowable load of 323 kN, corresponding to a 2.34 mm displacement (Figure 5).

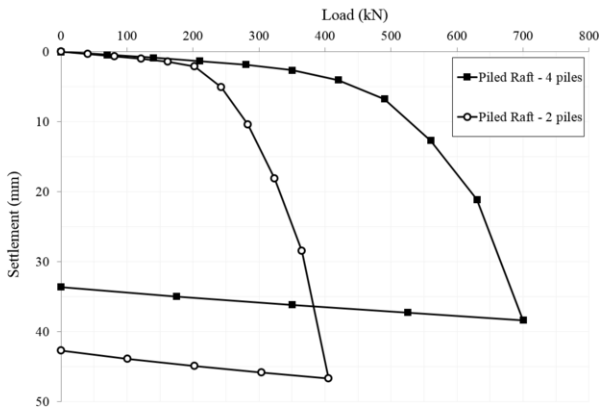


**Figure 5.** Load vs settlement curve for piled rafts.

The pile load transfer of the piled rafts showed the skin friction mobilization from the 1st to the 10th loadings, with increasing of the tip resistance along these loads (Figure 6). The skin friction and the tip resistance mobilization remained increasing as the applied loading, as observed the Figure 6. It should be noted that the loads presented on the top of the Figure 6 refer to the value subtracted from that referring to the contact of the raft with the ground.

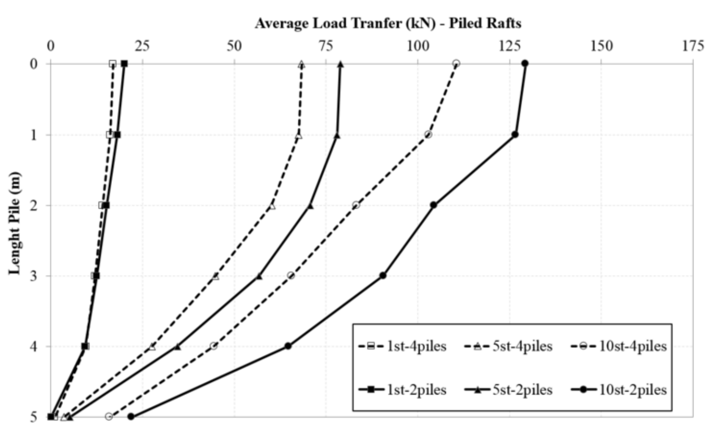


**Figure 6.** Load transfer curves for piles.

The load distribution between the shallow foundation (raft) and deep foundation element (piles) was recorded from the 1st stage of loading in which the piles contributes for 99 % of the load applied to the piled raft, compared to 1%, relative to raft / soil contact. From the 2nd stage, the participation by skin friction and tip resistance of the piles decreased gradually, concomitantly to the increase of the resistance due to raft / soil contact. In the 5th stage of loading, a load distribution of 78% (73% + 5%) was obtained, regarding the performance of the pile (tip resistance and skin friction); and 22 % of the load was absorbed by raft / soil contact. At the final loading, the pile accounted for 64 %, with 53 % for skinl friction and 11 % for tip resistante, against 36 % due to raft / soil contact.

Therefore, it is assumed that the load supported by raft /soil contact (net area) was 146 kN, equivalent to a resistance of 145 kPa. In the case of the piled raft composed of four piles the average resistante was 80 kPa. The load distribution between the surface (raft) and deep (piles) elements for the piles rafts presented similar results (Figure 7), as well as the distributions between the tip and skin friction (Figure 8). The greater participation of the tip resistance can be attributed to the influence of raft contact in the development of the skin friction of the piles in the first meters of soil close the base of the raft.

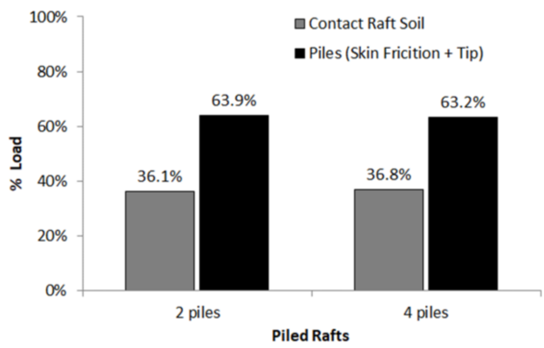


**Figure 7.** Raft / soil contact distribution.

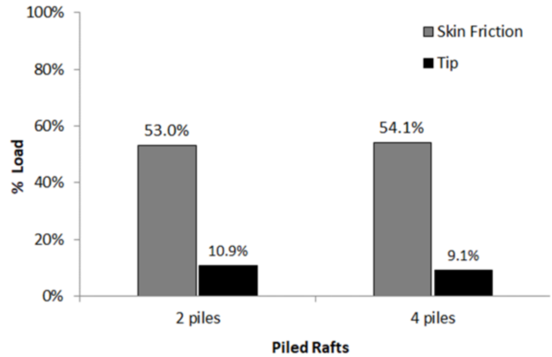


**Figure 8.** Pile load distribution.

When the foundation elements are analyzed separately, and in function of the respective settlement, it is verified that in both analyzed cases, the effect of the contact of the shallow foundation element (raft), provided an increase in the support capacity of the piled foundation (Figure 9 and Figure 10).

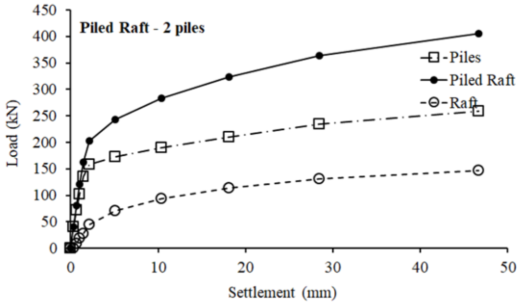


**Figure 9.** Load vs settlement curves - two piles.

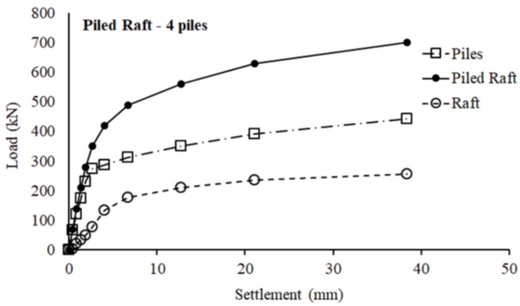


**Figure 10.** Load vs settlement curves - four piles.

The results presented distinct load *vs* settlement curves for piles, raft and piled raft. Note that the contribution of the contact of the raft is not significant for low values of settlements (2 mm). From this point, the load *vs* settlement curves of the piles and raft keep separately. It is observed the greater participation of raft contact in the load capacity of the foundation element, simultaneously to a significant settement increase (Figure 9 and Figure 10).

Regarding the inertia analysis for the raft plan secction, it is verified that there is influence under the stiffness of the surface foundation element and the kind in which it distributes the loads to the group of piles and to the soil. Despite this influence, the contribution due to the raft / soil contact observed was 36.0 % and 36.9 % for the piled foundations analyzed in this study, respectively (Figure 11).

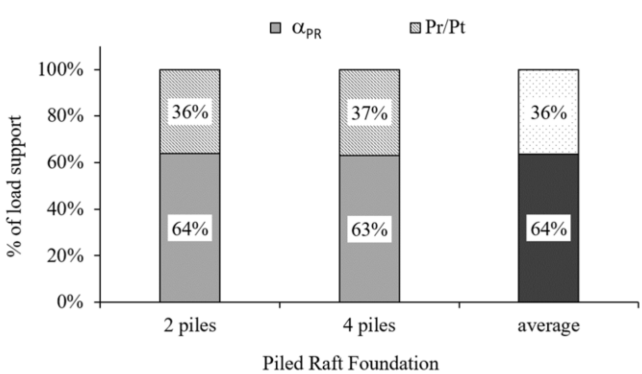


**Figure 11.** Contribution of the group of piles ($\alpha_{PR}$) and raft / soil contact.

## 4. Conclusions

Considering the analyses and discussions of this study, the following conclusions can be presented:

- Load capacity gains from the contact with the soil depends on its geomechanical characteristics, however, even for non-textbook soils which has high voids index, its important contribution to load capacity can be verified;
- For piled raft foundations composed of piles spaced with five times their nominal diameter, the contribution of contact was around 36%, showing that even for non-textbook soils, the raft /soil contact aids in improving load capacity and reducing the stress applied to the ground;
- The interaction factor obtained for the piled foundations showed different $\alpha_{rp}$ values from those observed by Clancy and Randolph [8], such difference can be attributed to geometry of the base of piled foundations used in this study, which were variable;
- The stiffness of raft interacting with the soil and the piles is influenced by the format (geometry) of the plan raft, impacting load absorption values through the contact raft /soil and raft / pile, and not only through the increase in the net area of contact and number of piles under the raft;
- In rafts with height able of making them stiff or semi-stiff, the raft / soil contact enables the technical and economical optimization of the geotechnical design, even for high loads, standardizing the structural load on top of the piles.

## Aknowledgements

The authors thank FAPESP ( São Paulo Research Foundation) for the support to the accomplishment of this article through the research project titled "Analysis of the behavior of piled raft in diabase soil of Campinas / SP Region", process 2011 / 17.959-3.

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