Influence of Pile-Soil-Raft Parameters on the Behavior of Piled Raft and Conventional Piled Group Foundations

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Abstract. In the Central Area of Brazil, particularly in the city of Goiânia (and in limited cases of the Brazilian capital Brasília), it is becoming common to observe in few foundation projects the design of a single, thick and large raft, supported by several piles, particularly for the central highly loaded and slender part of very tall buildings. In fact, many of these piles are designed as "settlement reducer" ones, behaving as "floating piles" with distinct geometries or relative pile stiffness (pile-soil) ratios. They are defined with basis on some rationalized procedure adopted to minimize the differential and total settlements of the raft, also based on its relative raft stiffness (raft-soil) together with aforementioned aspects. In such conditions, the calculation is usually done using a capacity and settlement based design approach that is normal in the case of "piled raft" foundation systems. Therefore, this paper aims to investigate this particular topic, scrutinizing numerical results of piled raft cases (and its comparison with "conventional" pile groups) under both cases of horizontal and vertical load conditions. It focuses on the influence of some key parameters of piled raft systems (related to overall pile, soil and raft geometric & mechanical characteristics) on their hypothetical design behavior. It further explores the possible advantages of designing under the concept of piled rafts under few particular conditions, yielding generalized conclusions from a "practical" point of view for those interested in such design methodology.
Keywords: piled raft, deep foundation, numerical analysis, parametric assessment, relative stiffness, displacement.

1. Introduction

In the heavily centered loaded portion of tall buildings under construction in the Central Area of Brazil, it may be now common to find a foundation designed with basis on a single raft supported by piles. This foundation raft generally encompasses several columns of the central projection of the building, and is structurally calculated to withstand shear, moment and concentrated loads under a combined set of conditions ("dead", "live", wind and "occasional" loads at distinct directions) set by Brazilian specific norms.

It is calculated also in geotechnical terms to withstand the same combination of loads, under two basic general guidelines recently set out by the Brazilian ABNT (2010) foundation Standard. This same standard allows the foundation to be designed as a conventional or standard "group of piles", as commonly done (so far) in the majority of foundation projects where no superstructure load is supported by the soil underneath the raft, or by the raft itself. Nevertheless, this standard also recognizes and allows the foundation to be designed as "piled raft", in which the contact of the base of the raft with the superficial soil can be taken on consideration - as long as the *overall* safety factor does not drop below advocated values.

One should however realize that the term "piled raft", as originally presented by Ottaviani (1975), Hain & Lee (1978), Mandolini & Viggiani (1997) and Poulos (1998), to name few key publications, is expressed in the present paper with the same definition as previously put forward by Janda *et al.* (2009). That means, as a "foundation system in which both structural components (piles and top raft) interact with each other and with the surrounding soil to sustain vertical, horizontal or moment loads coming from supported superstructures".

It is emphasized that this is valid independently if the piles of such system are designed as "settlement reducers" (as initially advocated by some authors) or not. Actually, according to Mandolini (2003), "piled rafts" refer to foundations that can be designed in any manner (under "capacity and settlement based design", "capacity based design" or as "differential settlement based design") as long as there is load sharing between the elements. That means that the understanding of the entire foundation system requires knowledge not only about the single pile interaction with the soil environment, but also the mutual influence of individual piles within the group plus the raft and the soil (the "foundation-structure" general interaction allowed in current designs by the new ABNT (2010) standard).

The paper therefore explores a parametric analysis of a nine floating pile group under a combined (non simultaneous) set of vertical and horizontal distributed loading, in contact and without contact with an idealized superficial soil layer. The analyses are carried out under distinct overall conditions, to be described.

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Submitted on September 8, 2011; Final Acceptance on April 25, 2013; Discussion open until August 30, 2013.

That means, under particular conditions of vertical and horizontal loading, it seizes the influence of the Poisson's Coefficient, the slenderness ratio[1]1 of the piles, the relative pile-soil and raft-soil stifnesses, and the soil contact type, in relation to typical design variables as the normalized displacement, the load sharing between raft and piles, and the distribution among (and along) piles at different positions.

The paper re-evaluates and further extends the outcome from an already published data within a past M.Sc. Dissertation Thesis from the University of Brasília (Bezerra, 2003), taking on account (and summarizing) some of the recent developments put forward by other publications in this same line of knowledge, as those from Sales *et al.* (1999, 2005), Cunha & Sales (1998), Cunha *et al.* (2000a, b & c, 2001, 2002, 2004, 2006), Bezerra *et al.* (2005), Cunha & Zhang (2006), Janda *et al.* (2009) and Ayala (2013), among others.

For instance, Janda *et al.* (2009) demonstrated that it is possible, although not straight forward, to simulate and generalize some key aspects of the behavior of piled raft and conventional foundation systems founded in rather complex soils (in their case, the Brasília "porous" clay), solely on the basis of numerical analyses of "typical" systems. They proved that the feasibility of the analyses for a future "real" design could be reached by using readily available parameters from pile load tests or site and laboratory investigations, allied to a good dose of common sense.

Thus, the objectives of this paper are rather the same as those from aforementioned authors, *i.e.* guidelines for the geotechnical behavior and for the design approach of such systems will be cautiously envisaged with basis on generalizations of parametric studies that encompass analyses of typical foundation setups. The systems, relative to piled raft and conventional groups, will be simulated under distinct conditions of overall geometry and soil/structural pile-raft mechanical values.

2. Numerical Model and Software

This paper adopts a numerical program developed exclusively for groups of deep foundations and piled rafts under general loading, named APRAFR, which was developed in the doctoral thesis of Zhang (2000) at University of Sydney. This program extends the "finite layer" method to accommodate a simultaneous general loading on top of piled raft foundations, allowing the establishment of coupled relationships between displacements (in all three directions), rotations (in two directions), and external loads. The origin of this method, and the adopted software, are briefly explained next.

2.1. Historical developments

Hain & Lee (1978) developed a method which considered the interactions of the piles, raft and soil, but the rotations and horizontal movements of a pile head induced by a vertical load applied to an adjacent pile or the soil surface were ignored. Soon later, Small & Booker (1984, 1986) and Booker & Small (1988) developed the finite layer method to analyze the behavior of stratified media of horizontal layers of finite thickness, when submitted to vertical loading. Hence, Lee & Small (1991) applied this theoretical method to the simulation of axially loaded piles founded in isotropic or cross-anisotropic elastic medium, where the nodes of the piles (intersection between horizontal soil layers and pile vertical surfaces) were stressed by annular uniform loads.

Ta & Small (1996, 1997) extended aforementioned models to developed a new numerical tool for the analysis of piled rafts (with the raft on or off the ground) and, as for Hain and Lee's method, the solutions were only for vertical loads. This method used finite elements to model the raft and the finite layer to model the soil, taking on account heterogeneity problems and system interactions.

Zhang & Small (2000a), subsequently surpassed the limitations from previous methods and developed a new numerical approach for the analysis of piled raft foundations, now subjected to both vertical and horizontal loadings. In this method, the interactions between raft and piles, raft and soil, piles and piles, piles and soil, and soil and soil were fully considered. However, the method could only deal with piled foundations clear of the ground, *i.e.*, "conventional" pile groups.

2.2. Establishment of the software APRAF

Zhang (2000) in his doctoral Thesis, and Zhang & Small (2000b) have introduced an extension of the method presented by Zhang & Small (2000a), where the raft could be in contact with the ground surface. Similarly as before, this approach uses a combination of the finite layer method for modeling the soil and the finite element method for simulating the raft and piles. The piled raft foundation can be subjected to horizontal and vertical loads as well as moments, and the movements of the piled raft in three directions (x, y, z) and rotations in two directions (x, y) may be computed by a program named APRAFR (analysis of piled raft foundations). In this program the raft could have any structural flexibility, and the stratified soil could have variable modulus along depth. Nevertheless the analysis still continued to be a linear elastic one. However, these authors have successfully made comparisons of the new solutions with those of the finite element method, and the effects of

1 Although the Merriam Webster on line dictionary defines "slenderness ratio" as the ratio of the length of a structural member (as a column) to its least radius of gyration, this ratio was defined herein as the relation between pile's length to diameter (L/D). One shall also notice that according to the New Webster's Dictionary "slender" means a thin, narrow or "week" element – which do contrast with the definition of this paper. A higher slenderness ratio (increase in L for a constant adopted d) does not necessarily mean a weaker pile.

parameters (adopted for soil and raft) on the behavior of piled rafts have been examined.

As shown in Fig. 1, reproduced from Zhang & Small (2000b), the problem of the piled raft foundation can be solved by assuming that the forces between the piles and layered soil can be treated as a series of ring loads applied to `nodes' along the pile's shaft. These loads are both horizontal and vertical. The contact stresses that act between the raft and the soil can be considered to be made up of uniform rectangular blocks of pressure approximating to the actual stress distribution. These can be considered uniform vertical blocks of pressure or uniform horizontal shear stresses. The displacement of the layered soil can then be computed, as the solution for a layered soil subjected to ring loads at the layer interfaces is found from finite layer theory.

Firstly, the response of the piles and soil (with no raft) is computed by applying unit surface loads to the rectangular regions on the ground surface, or unit ring loads to the soil along the pile's shaft, or a unit uniform circular load at the base of the pile. The deflections so computed can be used to form the influence matrix for the soil. For the piles, a stiffness relationship may be written based on shaft loads and on applied load at the pile heads. Three noded linear bending elements are used to model the piles.

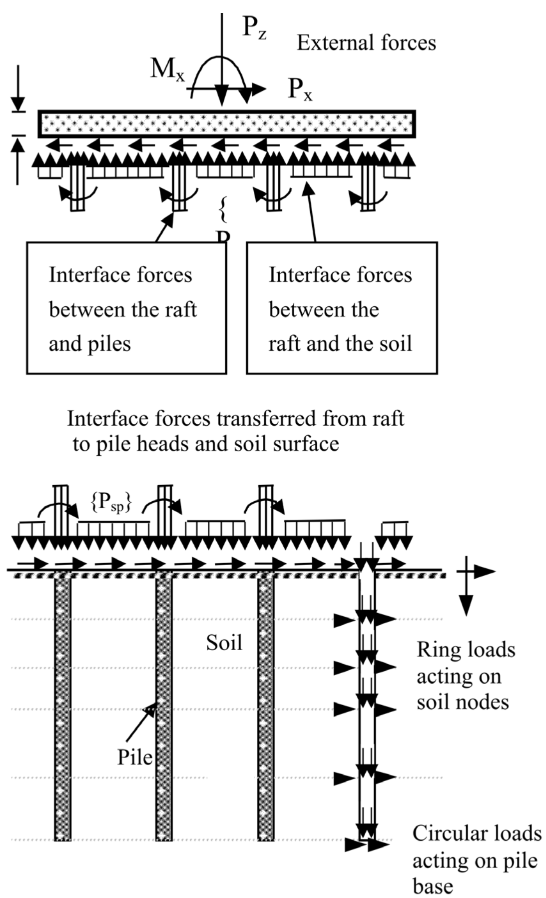

Figure 1 - Modeling of piled raft (modified after Zhang & Small (2000b).

Deflections of the soil or of the piles can be obtained for loads applied to the pile heads from the final stiffness relationship for the pile-soil continuum. This method is not as efficient computationally as computing the interaction between two piles only (*i.e.* by using the interaction factor method as advocated by Poulos, 1998 in his well known GARP software). However, it is much more accurate, especially for piles at close spacing because all the piles are considered at once.

Since the deflection of the piles can be computed when one is loaded at the head, or when the ground surface is loaded, this can be used to determine the behavior of the raft. Thus, by applying unit loads to the raft, its influence matrix may be obtained. By applying unit pressures to the ground, or unit pressures and moments to the pile heads, an influence matrix for the soil-piles may be obtained.

Finally, by considering equilibrium of applied forces and moments acting on the piles and raft, and compatibility of displacements of the soil and raft (and of displacement and rotation of the pile head and raft) enough equations may be assembled to obtain the solution under general loading. One should realize that there is full displacement compatibility between raft and soil, hence, no "soil-slip" at interface can be assumed.

3. Analyses and Results

The previously cited solutions were incorporated within the APRAFR software, used in this paper to perform a series of parametric analyses to be described and discussed now. Generalized conclusions, although limited somehow for the studied cases, are also provided.

3.1. Set up of the problem

The study of piled raft foundations involve a great range of interdependent variables that form a complex problem that, most of the time, is necessary to be solved with the adoption of some simplified hypotheses and/or configurations. A certain set of parameters is also needed to set up a model to study the system's behavior. So, using simple elements it is possible to depict in Fig. 2 the overall aspects of the systems which were simulated herein.

In this figure it is noticed the square layout of the raft and the position of the piles, in plan view, and a particular cross section in mid-position of the raft with the respective pile and soil profiles. A closer view of a small insert shows in detail the denomination used for distinct pile positions within the raft, from corner to center type locations.

The main difference in Fig. 2 from piled rafts and conventional group systems is the raft/soil contact, which is inexistent in the latter case and present (physically bonded via nodal points) in the former one.

Table 1 complements the information from aforementioned figure, stating the main physical parameters adopted in the analyses, and their ranges and magnitudes.

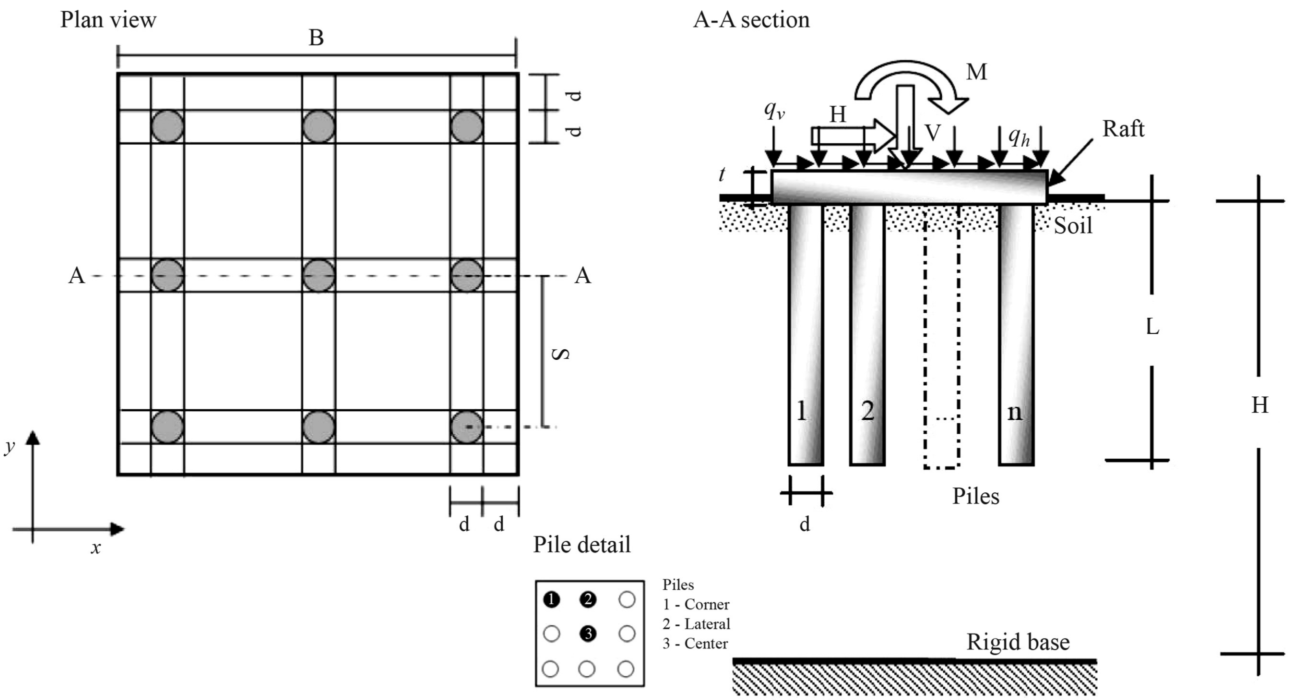

Figure 2 - Layout of the studied foundation system (modified from Bezerra, 2003).

They were originally established from standard geometric configurations and soil-raft values backanalyzed in Cunha & Sales (1998) field load tests at the Research Site from the University of Brasília, and later on from Sales (2000) and Cunha *et al.* (2004), as they may relate to standard values of interest to be regionally adopted for the design of such structures.

Besides, the range of variation for the parameters was selected to fit within magnitudes from a previous (and classical) similar exercise presented by Clancy & Randolph (1993), where squared piled rafts up to 36 piles were thoroughly simulated.

It shall be noted in Table 1 that the following equations do apply:

$$K_{RS} = \frac{4\, E_R\, t^3\,[1-\nu^2]}{3\pi\, E_S\, B^3\,[1-\nu_R^3]} \tag{1}$$

in accordance to Brown (1975) for square (B x B) rafts, where all the parameters are specified in this same table.

$$I_\alpha = \frac{E_S\, d\,u_\alpha}{q_\alpha\, B^2} \tag{2}$$

a non-dimensional variable, where α refers to vertical (v) or horizontal (h) directions. I_α is the normalized displacement, u_α is the displacement at the center of the raft, and q_α the distributed stress on the raft.

$$\Delta = \frac{u_{v-corner}}{u_{v-center}} \tag{3}$$

a non-dimensional differential settlement ratio based on vertical displacements in distinct pile positions, in accordance to the detail in Fig. 2. In other words, the higher is the value of Δ the more homogeneous or uniform are the settlements around the raft, and vice versa.

Therefore, for the appreciation of the key design aspects of the problem, as it was set up in this paper, the main (output) variables of interest, as settlement or shared load of the piles, were obtained and plotted. The results are presented and discussed along the next figures. Similarly as Fig. 2, all the subsequent ones have also been thoroughly modified after the original data published in Bezerra (2003).

3.2. Cases of load in the vertical direction

This item and respective sub items deal exclusively with comparisons between piled raft and standard group systems under vertical distributed load, for distinct values of the pile slenderness ratio (L/d). The influence of the key parameters L/d, ν, K_{RS}, K_{PS} and foundation system are evaluated and discussed.

3.2.1. Effect of L/D, ν and foundation type

The effect of some initial parameters of design respectively on the normalized central settlement and on the percentage of load absorbed by the pile group (the remainder goes to the raft alone), can be visualized through Figs. 3

Table 1 - Adopted parameters in analyses.

Parameter	Value
Soil Young Modulus E_S	6 MPa
Structural Young Modulus of Pile (E_P)	18000 Mpa and variable (600-6000000)*
Structural Young Modulus of Raft (E_R)	20000 MPa
Number of piles (n)	9
Soil Poisson's Coeff. (ν)	0.35 and variable (0.1-0.5)**
Structural Poisson's coeff. of Pile (ν_P) and Raft (ν_R)	0.2
Pile length (L)	Variable 12.5-50 m
Pile diameter (d)	0.5 m
Pile spacing (S)	2.5 m
Position of rigid base (H)	10 times L
Raft breadth or length (B)	6 m
Raft thickness (t)	0.5 m and variable (0.25-1.25)***
Pile spacing ratio (S/d)	5
Depth along pile's Shaft (z)	Variable 0 to L
Pile slenderness ratio (L/d)	Variable 25 to 100
Pile-soil stiffness ratio ($K_{PS} = E_P/E_S$)	Variable 100-1000000
Raft-soil stiffness ratio (K_{RS})	Variable 0.1-12
Distributed vertical stress on raft (q_v)	0.1 Mpa
Distributed horizontal stress on raft (q_h)	0.1 MPa
Normalized central settlement in vert. direction (I_v)	Result in accordance to Eq. 2
Normlzd. central displacement in horizontal direction (I_H)	Result in accordance to Eq. 2
Differential settlement ratio in vertical direction (Δ)	Result in accordance to Eq. 3

Observations:
(1) V Load = load in vertical direction;
(2) H Load = Load in horizontal direction;
*Variable in plots with the K_{PS} parameter;
**Variable in plots with the ν parameter;
***Variable in plots with the K_{RS} parameter and Eq. 1.

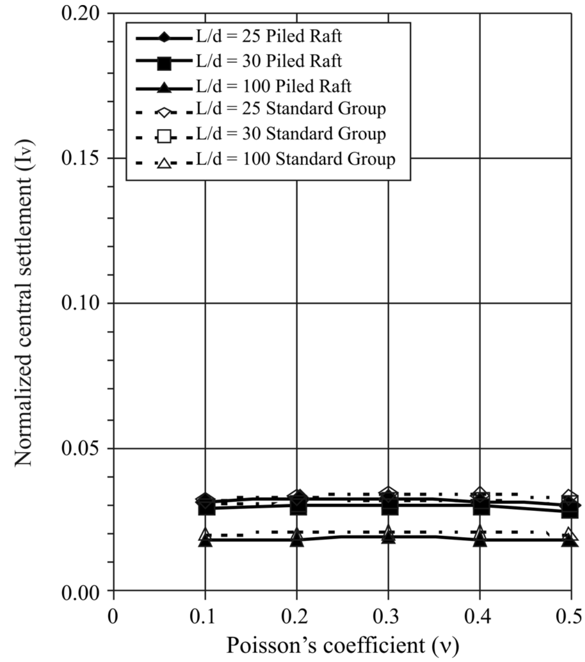

Figure 3 - Effect of the variation of some initial parameters on the settlement value.

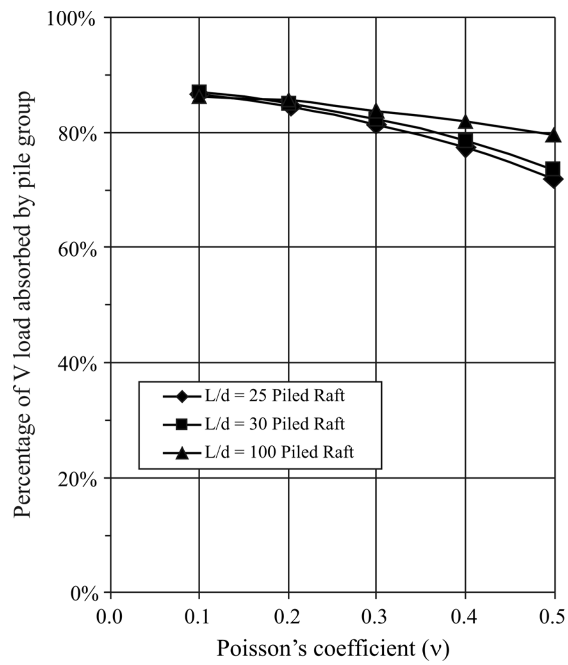

Figure 4 - Effect of the variation of some initial parameters on the load distribution.

and 4. It is noticed that such comparisons were carried out in terms of a constant E_P of 18000 MPa (K_{PS} = 3000) and raft thickness of 0.5 m, besides of distinct L/d, as previously mentioned, with a range from 25 to 100 that covers most practical cases. The Poisson's Coeff. varied from 0.1 to 0.5, and all other parameters are in accordance to Table 1.

From this set of figures, the following main observations can be drawn:

- The sensitivity of the vertical normalized central settlement to variations in ν is negligible for both cases of system;
- Piled raft systems do not appear to have a noticeable advantage in comparison to standard groups in terms of the reduction of the vertical total settlement of the raft;

- The pile slenderness ratio has more influence on the derived normalized settlement than the Poisson's Coeff., again for both cases. Also, the higher is *L/d* the lower will be the settlement;
- In the case of piled rafts only, the influence of the Poisson's Coeff. on the percentage of load absorbed by the piles is low. For practical (medium) values of ν, this influence tends to be rather small;
- However, differently as before, the higher is *L/d* the higher will be the load absorbed by the pile group within a piled raft system.

Given such observations, one can yield the following partial conclusions strictly valid to vertical loading:

- In design projects with either piled rafts or standard pile groups under vertical distributed load the estimation of the Poisson's Coefficient is not of concern, particularly when the interest is in the total central settlement of the system, or the load share within its elements;
- In order to decrease (to a low degree) the vertical settlement for both systems, the slenderness ratio of the pile shall be increased. This procedure will also lead, in piled raft systems, to a slight increase in the load absorbed by the piles, in detriment (*i.e.* with corresponding decrease) of the raft's load;
- If the major design interest is in the total vertical central settlement of the raft, there is no advantage in designing the foundation as a piled raft system.

3.2.2. *Effect of the pile-soil stiffness ratio*

The effect of the relative Pile-Soil stiffness ratio (K_{PS}), *i.e.* the relation between the Young modulus of the pile (E_P) and of the soil (E_S) was also evaluated in regard to the normalized central settlement and to the percentage of load absorbed by the pile group, among other variables. Similarly as before, this was carried out for both piled raft and standard group systems with. Such comparisons were carried out in terms of a constant ν of 0.35, raft thickness of 0.5 m, besides of distinct *L/d*, as previously commented. The E_P of the pile varied from 600 to 6000000 MPa in order to respectively yield K_{PS}'s from 100 to 1000000. All other parameters in accordance to Table 1.

Figures 5 and 6 show aforementioned results, again in terms of distinct slenderness ratios ranging from 25 to 100. From the analyses, it is possible to observe that:

- The sensitivity of the vertical normalized central settlement to variations in K_{PS} is more pronounced, in both systems, for relatively "deformable" or ordinary pile cases, *i.e.*, piles with relative stiffness ratios around and lower than 1000. In this regard, the higher is the compressibility of the pile (the lower is K_{PS}) the higher is the normalized vertical settlement. On the other hand, for less deformable or "incompressible" piles (very high K_{PS}), the influence of K_{PS} is negligible;
- The pile slenderness *L/d* ratio does not appear to have pronounced influence on the derived normalized settlement for more compressible piles (ratios ≤ 1000). For less compressible or incompressible piles, the influence of this ratio is of note, and similar for both systems, that means, the higher is *L/d* the lower will be the settlement;
- In the case of piled rafts only, the influence of K_{PS} on the percentage of load absorbed by the piles is low for in-

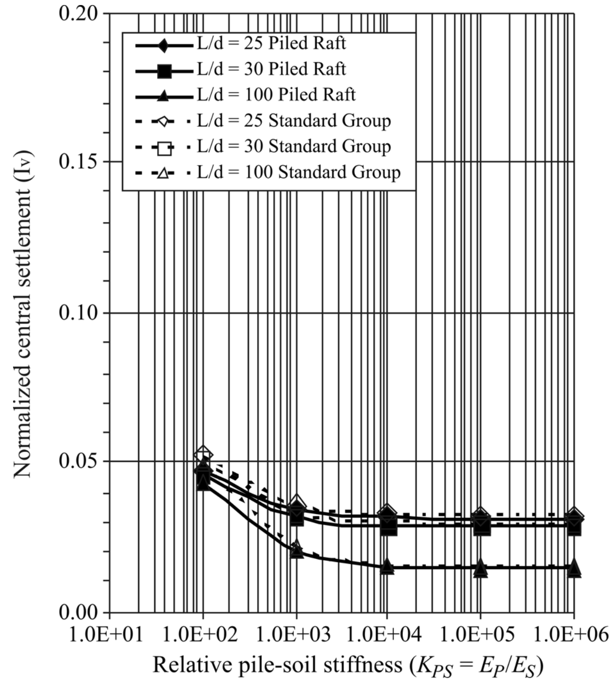

Figure 5 - Effect of the variation of the Relative Pile-Soil stiffness on the settlement value.

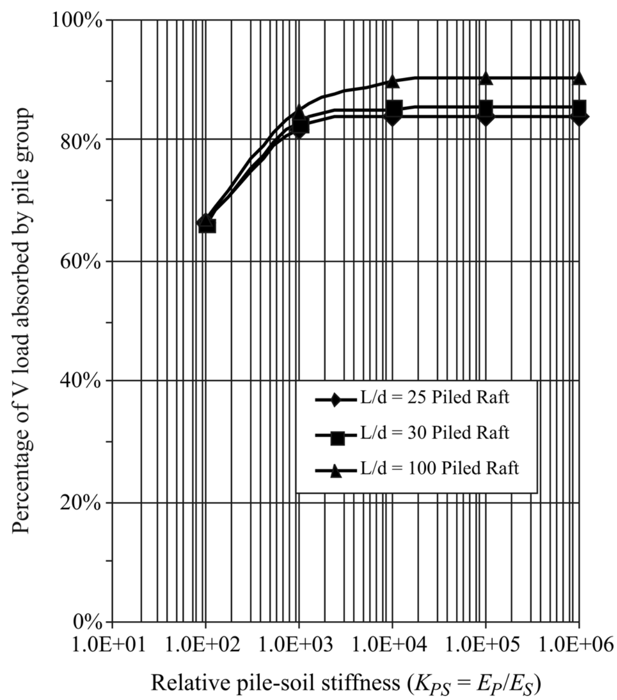

Figure 6 - Effect of the variation of the Relative Pile-Soil stiffness on the load distribution.

compressible piles. For more compressible ones, the higher is the compressibility of the pile (the lower is K_{PS}) the lower will be the load absorbed by the pile elements (more load to the raft). Besides, *L/d* slenderness ratio has only influence on incompressible piles, increasing their absorbed loads with the increase of *L/d*;

- It is finally noticeable the inverse correspondence of results from absorbed load and settlement in the range of incompressible piles, for piled raft systems.
- The effect of the relative Pile-Soil stiffness ratio (K_{PS}) concerning the differential settlement ratio (Δ) is presented in Fig. 7 for both systems. In this figure it is possible to notice that:
- Similarly as the vertical normalized total settlement, Δ is also very sensitive to variations in K_{PS}, in both systems, for relatively "deformable" pile cases. Again, the higher is the compressibility of the pile (lower is K_{PS}) the lower is the differential settlement ratio (less uniform settlements). For incompressible piles there is no influence of K_{PS}, *i.e.*, and the settlement of the raft becomes much more homogeneous (higher values of Δ);
- The pile slenderness *L/D* ratio does not appear to have a pronounced influence on Δ in all spectrum of K_{PS} variation, although some slight tendency of the decrease of Δ with the increase of *L/D* may be observed for piles that are more compressible;
- Both foundation systems have similar values of Δ varying with K_{PS}, although slight higher (Δ) numbers were obtained for the standard groups, *i.e.*, this latter system allowed slightly more uniform settlements along raft;

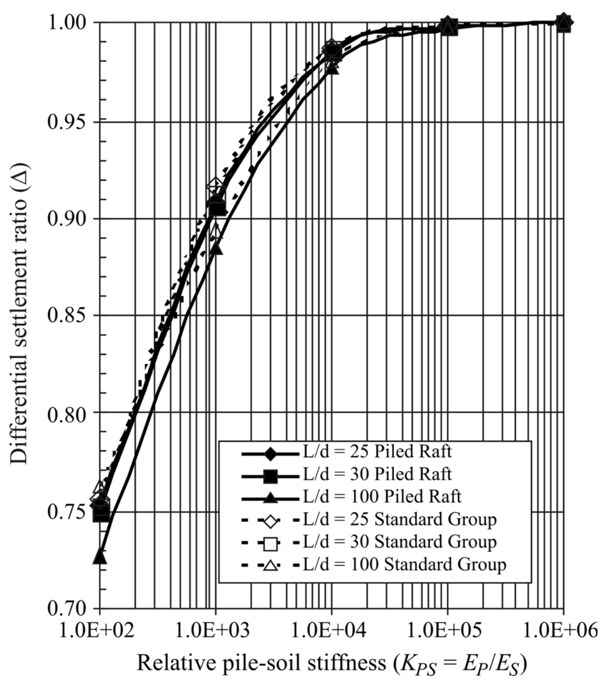

Figure 7 - Effect of the variation of the Relative Pile-Soil stiffness on differential settlement.

- All aforementioned aspects and trends have been similarly obtained by Zhang (2000), and by Clancy & Randolph (1993) (regarding normalized central settlement), in their numerical analyses.

Taking on account the detailed group configuration from the insert of Fig. 2, it is now possible to evaluate the load distribution within the piles of each system (in percentage to the total) in relation to variations on the relative Pile-Soil stiffness ratio. Figure 8 (a) and (b) respectively presents the results for a piled raft and a conventional group system, in regard to corner, center or laterally positioned piles.

From this one, it is noted the following points:

- The percentage of vertical load absorbed by the piles in each particular position is similar irrespective of the system. The piled raft, however, allows slightly less load to be transmitted to the piles, as part of the total applied load is absorbed by the raft;
- The load distribution concerning the pile's position is also a function of the relative Pile-Soil stiffness. For instance, for more compressible piles, where (as noticed before) total settlements are higher and differential ones more pronounced, the load at each position tends to be more uniform and similar. For less compressible, or incompressible piles, where differential settlements tends to be homogeneous along the raft, it is clear that center piles take lesser loads than lateral ones, and this one lesser loads than corner piles - the latter absorbing the highest load. Besides by decreasing the compressibility of the piles (hence increasing K_{PS}) the center piles will tend to slightly decrease their share of load in detriment to corner piles;
- In regard to the pile's slenderness ratio, it is also clear that, in the case of an incompressible pile, an increase of this ratio will tend to turn more "uniform" the loads within the pile elements (for both cases). That means, by increasing the pile's *L/D* center and lateral piles (those with lower loads) will tend to increase their share of load in detriment to corner piles (originally with higher loads), which on the other hand will tend to decrease their share of load.

Given such observations, one can yield the following partial conclusions, strictly valid for vertical loading:

- The adoption of a particular relative pile-soil stiffness ratio has the same effect for both piled raft and standard group systems when the main variable of interest is either the differential vertical settlement of the raft or the percentage of load absorbed by the piles. Although the piled raft system allows less load to be transmitted to the piles, as the raft shares part of the load, it does not seem to be so advantageous in design in comparison to standard groups, as both systems yielded similar values of normalized central and differential raft settlements;
- Nevertheless, if a piled raft is adopted one should try, whenever possible, to increase the relative stiffness of

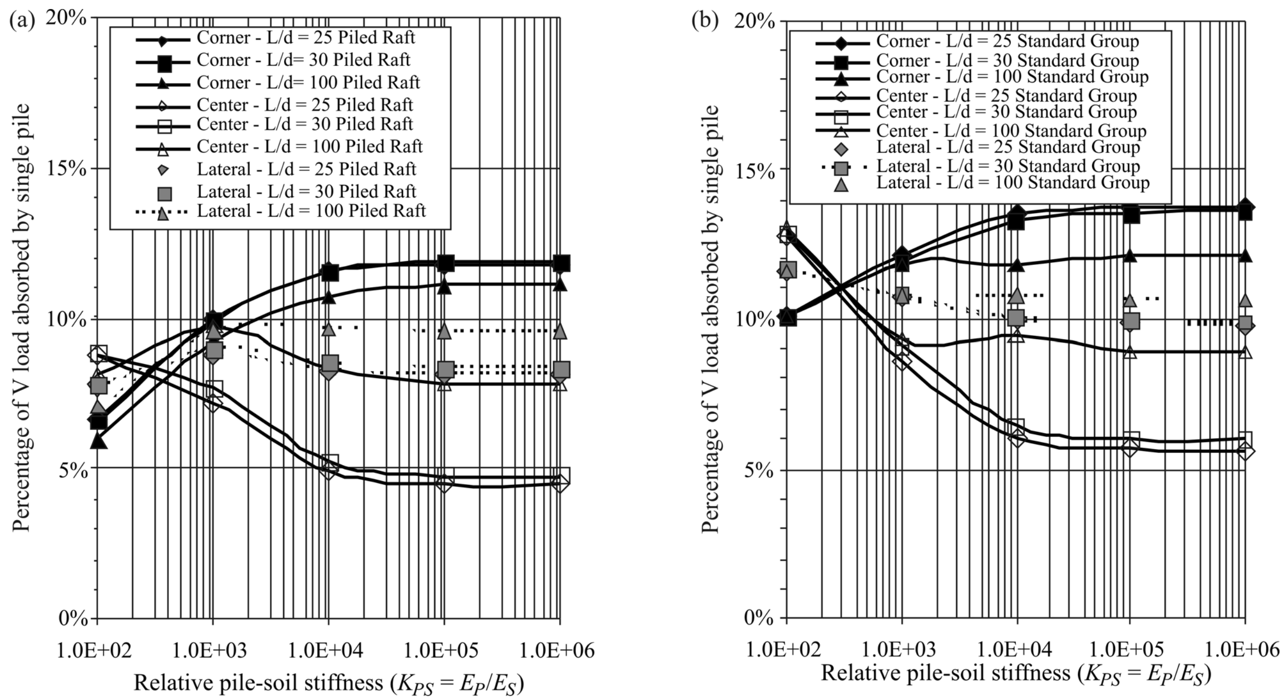

Figure 8 - Effect of the variation of the Relative Pile-Soil stiffness on the single pile's load for (a) piled raft and (b) conventional pile group.

the pile in regard to the surrounding soil (if possible with $K_{PS} > 1000$, *i.e.* turning the pile less deformable). As the results show, an increase of K_{PS} beyond a given value does not significantly influence both results of settlement and absorbed loads;

- By designing piled rafts with incompressible piles, one should also try to increase their slenderness ratios, since there will be a positive tendency of reduction of the total central settlement of the system with the increase of *L*/*D*, although the influence on the differential settlement will be negligible. Nevertheless, this will also lead to a corresponding increase of the absorbed load from the piles (with simultaneous decrease of raft's load);
- In terms of load share within the elements of the system, by adopting incompressible piles and by allowing them to have high slenderness ratios (if practical, much above 30), it is possible to obtain foundation systems with more uniform loads. Perhaps, by having center and lateral piles with higher *L*/*D* than corner piles, such effect could be maximized (although it was not tested herein). Anyway, this "rationalized" design concept (some define it as an "optimization") has already been advocated before by Cunha *et al.* (2001), Reul & Randolph (2004) or Bezerra *et al.* (2005) among others, and is the next step in designing piled rafts.

3.2.3. Effect of the Raft-Soil Stiffness ratio

The effect of the relative Raft-Soil stiffness ratio (K_{RS}) was also done with the same variables studied before. Such comparisons were carried out in terms of a constant ν of 0.35 and E_P of 18000MPa (K_{PS} = 3000), besides of distinct *L*/*D*, as previously commented. All other parameters in accordance to Table 1.

The value of K_{RS} for each situation was calculated via Eq. 1 with the same parameters of Table 1, and a variable raft thickness (*t*) which varied from 0.25 to 1.25m in order to respectively obtain a range of K_{RS} from 0.1 to 12. That means, from very flexible rafts (≤ 0.1) to rigid or "incompressible" ones (≥ 10).

Figures 9 to 11 respectively present the results in terms of the normalized central settlement, the percentage of vertical absorbed load by the group, and the differential settlement ratio.

From these figures, the following comments apply:

- The sensitivity of the vertical normalized central settlement to variations in K_{RS} is negligible throughout the spectrum of stiffness variation. However, it is affected in the same manner by the pile slenderness ratio *L*/*D* for both systems, that means, the higher is *L*/*D* the lower will be the settlement at any stiffness ratio. In fact, according to Zhang (2000) in analyses for standard group systems, "the E_R/E_S stiffness ratio has only a minor effect on the vertical deflection" and "increase in pile length will greatly reduce the vertical displacements". Curiously according to this author this stiffness ratio seems to be more influential in reducing horizontal deflections rather than vertical ones, nevertheless this topic will not be covered later herein;

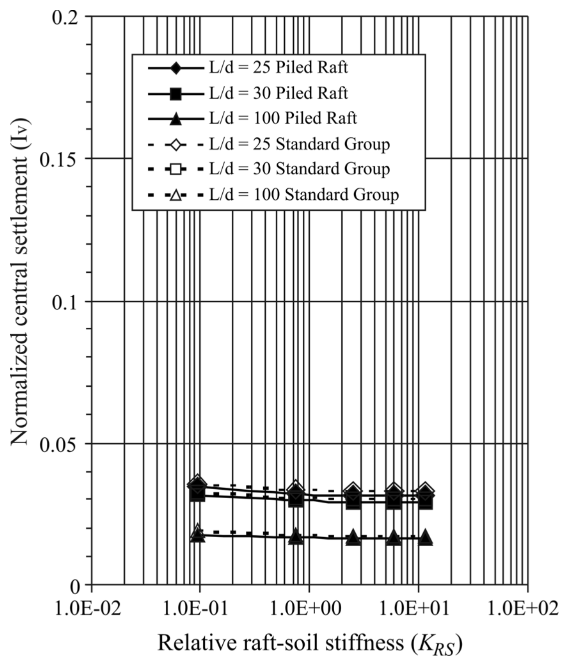

Figure 9 - Effect of the variation of the Relative Raft-Soil stiffness on the settlement value.

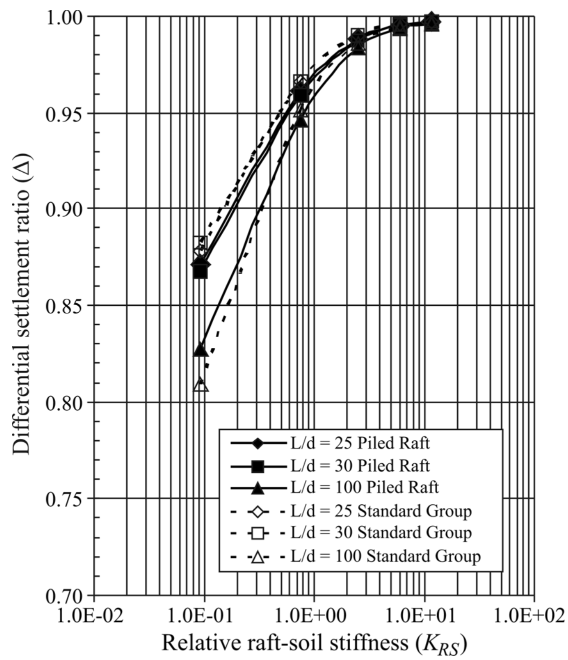

Figure 11 - Effect of the variation of the Relative Raft-Soil stiffness on differential settlement.

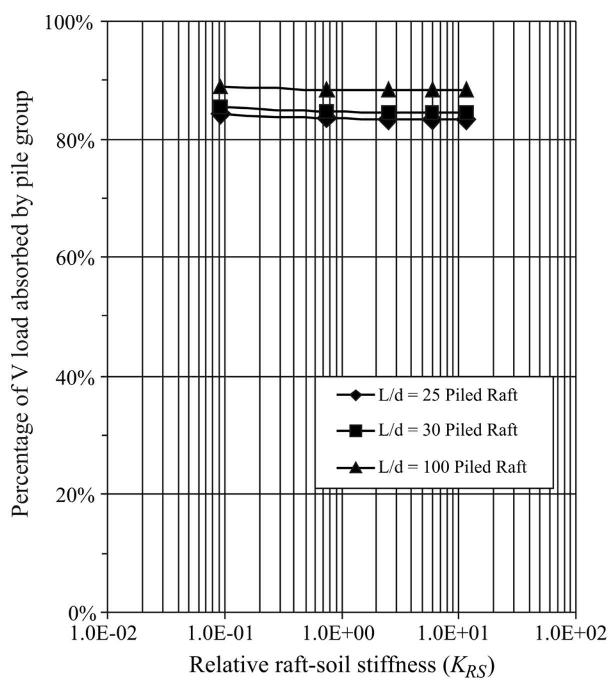

Figure 10 - Effect of the variation of the Relative Raft-Soil stiffness on the load distribution.

- On the other hand, the differential settlement ratio (Δ) is very sensitive to variations in K_{RS}, in both systems and for flexible rafts, *i.e.*, the higher is the flexibility (lower is the K_{RS}) the greater are the differences between the settlement at the corner and at the center of the raft (lower values of Δ), with the corner's settlement being always lower. For rigid rafts there is no influence of K_{RS} in both systems, *i.e.*, an increase of K_{RS} beyond a given value does not significantly influence the results;
- Differently to what has been noted in the case of the pile-soil stiffness, for K_{RS} it also seems that there is a more clear influence of the slenderness *L*/*D* ratio on Δ, for both system cases, when the raft is flexible. In this case, the higher is the pile slenderness ratio *L*/*D* the greater will be the differences between the settlement at the corner and at the center of the raft (*i.e.* the lower are the Δ values). For rigid rafts such effect is of negligible magnitude;
- In the case of piled rafts only, the influence of K_{RS} on the percentage of load absorbed by the piles is low or inexistent for any flexibility of the raft. Nevertheless, by increasing the *L*/*D* slenderness ratio there will be an increase of the absorbed load by the piles, with consequent fewer load being transferred to the raft.

Similarly as the previous sub item, the evaluation of the load distribution within the piles of each system is presented at this stage, now in relation to variations on the relative Raft-Soil stiffness ratio.

Hence, Fig. 12 (a) and (b) respectively show the results for a piled raft and a conventional group system, in regard to corner, center or laterally positioned piles.

From this figure some main observations can be given, as follows:

- Load distribution in regard to the position of the pile is influenced by the relative Raft-Soil stiffness. For instance, for flexible rafts, where differential settlements are more pronounced, the load at each position tends to

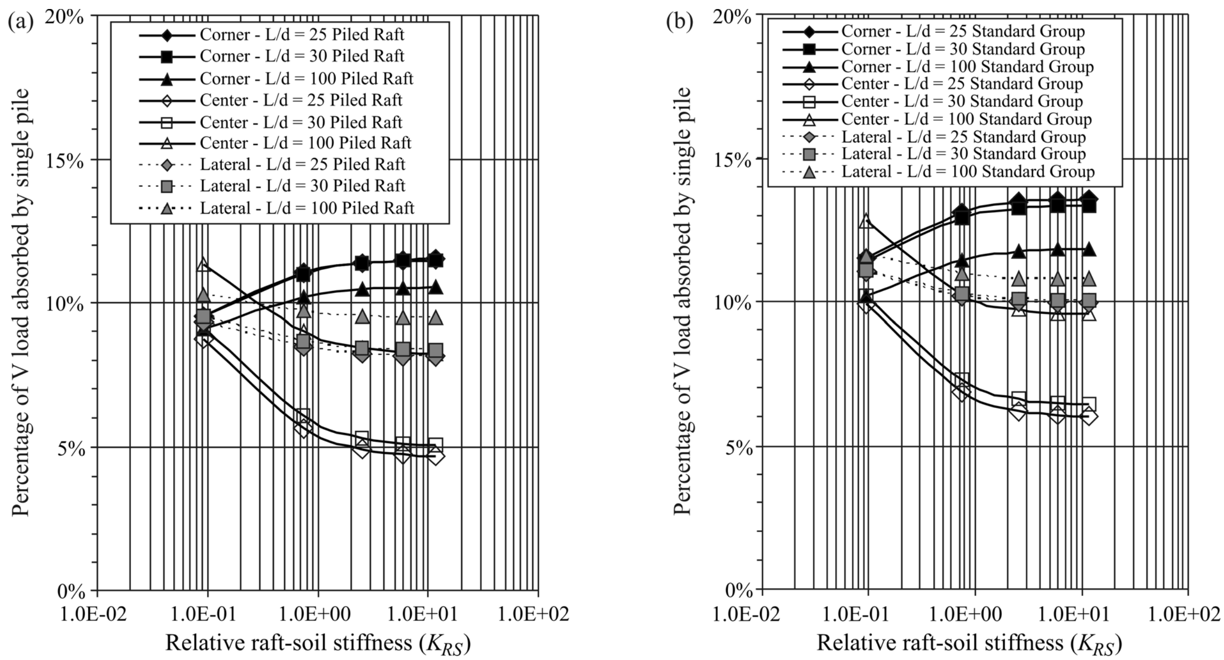

Figure 12 - Effect of the variation of the Relative Raft-Soil stiffness on the single pile's load for (a) piled raft and (b) conventional pile group.

be more uniform and similar (especially for $K_{RS} = 0.1$) than the equivalent one at respective positions in rigid rafts. For rigid rafts it is clear that center piles takes lesser loads than lateral ones, and this one lesser loads than corner piles - the latter absorbing the highest load (same observation as given for K_{PS});

- In relation to the pile's slenderness ratio, it is also clear that, in the case of a rigid raft (with more uniform settlements), an increase of this ratio will tend to homogenize the loads within the system elements (for both cases). In a similar way as depicted for K_{PS}, by increasing the pile's L/D ratio, center and lateral piles (with lower loads) will tend to increase their share of load in detriment to corner piles.

Partial conclusions can also be given with aforementioned observations, as it will be detailed next. Again, they are strictly valid for vertical loading:

- The adoption of a particular relative raft-soil stiffness ratio has the same effect for both piled raft and standard group systems when the main variable of interest is either the total or the differential vertical settlement of the raft;
- In any case one should always try, whenever possible, to increase the relative stiffness of the raft in regard to the supporting soil, turning the raft rigid. For engineering purposes, a value of K_{RS} equal or higher than 10 is enough to ensure practically uniform settlements within the raft;
- Nevertheless, by designing with flexible rafts one should be aware that by increasing the pile's slenderness ratio to values as high as 100 there will be a simultaneous decrease of the central settlement of the raft with a slight increase of its differential ratio (difference between corner and center displacements);
- In the case of rigid rafts it is advantageous to increase the pile's slenderness ratio, as it will decrease total settlements without collateral effects on the raft's differential values. In the case of piled rafts, this will also lead to a corresponding increase of the absorbed load from the piles (with simultaneous decrease of raft's load);
- In terms of the load share within the elements of the system, for both standard groups and piled rafts, it is possible to obtain a more uniform load distribution among the piles by allowing the raft to be rigid ($K_{RS} \geq 10$), and by designing with piles with high slenderness ratios. Such homogenization can also be achieved with very flexible rafts (at any pile's L/D ratio), but with the disadvantage of larger differential settlements within the raft.

3.3. Cases of load in the horizontal direction

This item is similar to the previous one, with the difference that it will now deal exclusively with load in the horizontal direction. The same magnitude of distributed stress (0.1 MPa) used in the (preceding) vertical cases was adopted here, as one notices in Table 1. However, in order to simplify the comparisons, and to cross compare the results to the vertical case, a unique slenderness ratio of 30 was adopted.

3.3.1. Effect of Poisson's coefficient

In a similar fashion as the previous data, the analyses carried out herein have also demonstrated that the influence of this parameter is negligible, and therefore can for all purposes be fixed in a foundation design. Similar results as those from former Figs. 3 and 4 have been obtained, and are not included in order to save paper's space.

3.3.2. Effect of the Pile-Soil Stiffness ratio

The effect of the relative Pile-Soil stiffness ratio K_{PS} was also evaluated concerning the horizontal load direction.

Their influence was assessed on the normalized central displacement (Eq. 2) and on the percentage of load absorbed by the pile group, as can be respectively visualized through Figs. 13 and 14.

From these figures one notices that:

- The sensitivity of the horizontal normalized central displacement to variations in K_{PS} is noticeable along all spectrum of relative pile stiffness, being more pronounced for standard pile groups than for piled rafts. Similarly as the vertical case, the higher is the compressibility of the pile (lower K_{PS}) the higher is the normalized horizontal displacement;
- On the other hand, in the horizontal direction piled raft systems do have a noticeable advantage in comparison to standard groups in terms of the reduction of the horizontal total displacement of the raft, as one observes in Fig. 13. This fact relates to the high percentage of load that is absorbed in the contact raft/soil, that, according to Fig. 14, ranges from around 80 to 35% (respectively from K_{PS} = 100 to 1000000). See for instance in Fig. 6 that in the vertical case the percentage of load absorbed by the raft was much lesser than in the horizontal one for all spectrum of K_{PS};

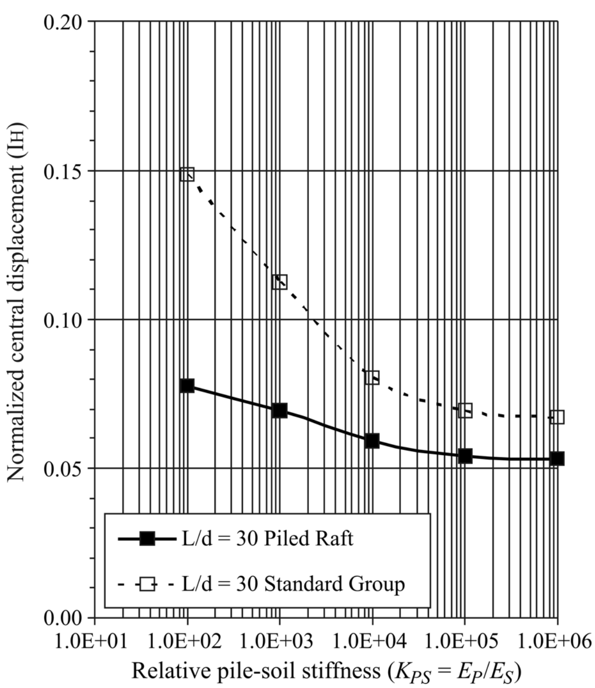

Figure 13 - Effect of the variation of the Relative Pile-Soil stiffness on the displacement value.

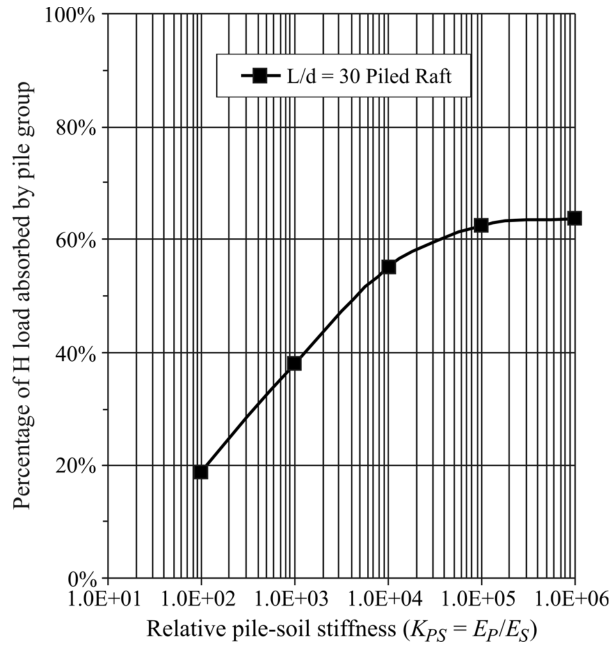

Figure 14 - Effect of the variation of the Relative Pile-Soil stiffness on the load distribution.

- It also seems in the case of piled rafts, comparing both situations of vertical and horizontal load at an equivalent K_{PS} (respectively at Figs. 5 and 13), that the lower is the load in the raft alone the lower will be the magnitude of displacement (in any direction);
- All aforementioned aspects and trends have been similarly obtained by Zhang (2000) in his analyses.

Taking on account the detailed group configuration from the insert of Fig. 2, it is also possible to evaluate the horizontal load distribution within the piles of each system (in percentage to the total) in relation to variations on the relative Pile-Soil stiffness ratio. Figure 15 (a) and (b) respectively presents the results for a piled raft and a conventional group system, in the same fashion as done for the vertical load.

From Fig. 15, one notices that:

- The trend of horizontal load distribution by the piles in each particular position is similar irrespective of the system. It is clear that center piles take lesser loads than lateral ones, and this one lesser loads than corner piles - the latter absorbing the highest load, in a similar fashion as observed for the vertical loading. Likewise, the piled raft allows slightly less load to be transmitted to the piles, as part of the total applied load is absorbed by the raft;
- The load distribution concerning the pile's position is a function of the relative Pile-Soil stiffness for both systems. For more compressible piles, where normalized horizontal displacements are higher, the load at each position tends to be more uniform and similar. For incompressible piles, the differences between the loads at each pile position are more pronounced and less uniform;

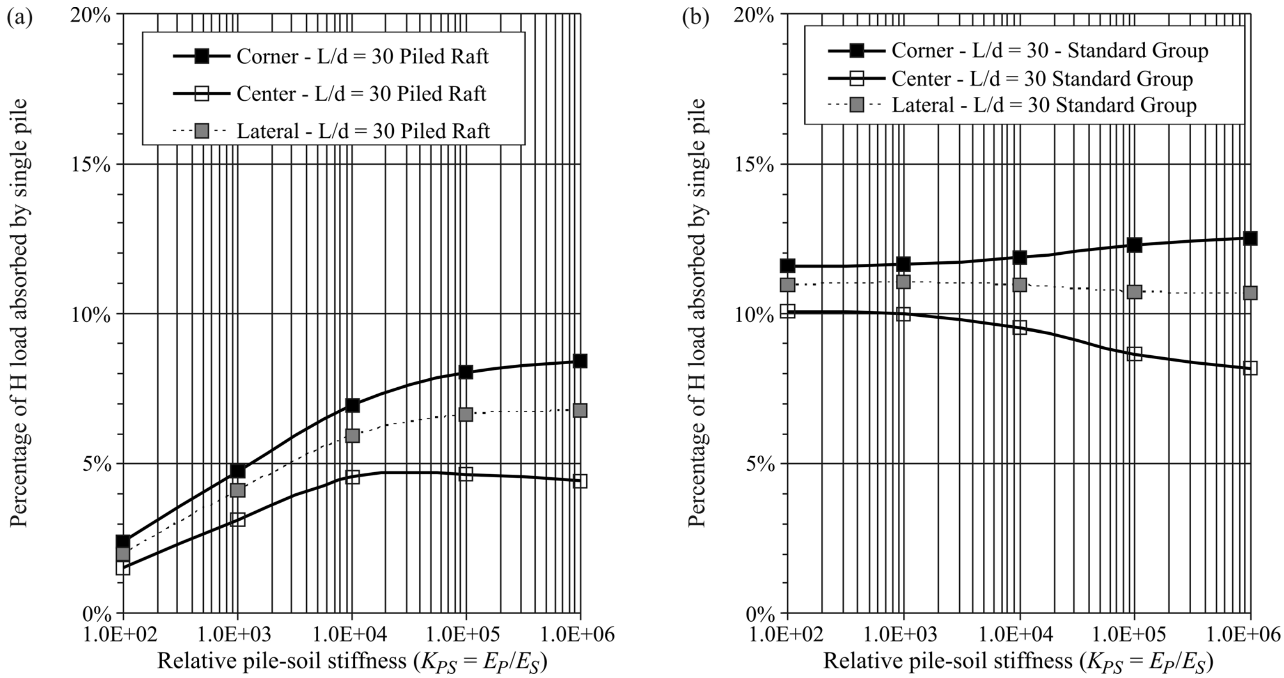

Figure 15 - Effect of the variation of the Relative Pile-Soil stiffness on the single pile's load for (a) piled raft and (b) conventional pile group.

- When comparing the situations of vertical and horizontal load shares at distinct pile positions with equivalent situations for both piled rafts and standard groups (respectively at Figs. 8 and 15), one notices that by decreasing the compressibility of the piles (hence increasing K_{PS}), center piles (those with lower loads) tend to decrease their share of load in detriment to corner piles (originally with higher loads). This will turn the load distribution more non-uniform within the system - as previously stated.

Given such observations, one can yield the following partial conclusions, strictly valid for horizontal loading:

- If the main variable of interest is the normalized central displacement of the raft it is of upmost importance to design the foundation as piled raft, with piles of high relative pile-soil stiffness K_{PS}, *i.e.* incompressible piles. This procedure will tend to decrease the horizontal displacements with a simultaneous decrease of the load being transferred to the raft. Nevertheless it will also induce a more non-uniform distribution of the (remaining) load within the piles of the system, with corner piles taking more load than center ones;
- On the other hand, if the system is designed as a standard pile group, it is also important to adopt incompressible piles in the project, besides of the aforementioned non uniformity of load distribution;
- In design projects with either piled rafts or standard pile groups under horizontal distributed load the estimation of the Poisson's Coefficient is not of concern.

3.4. Load distribution along pile

Figures 16 and 17 depict the load distribution along the shaft at distinct relative depths (z/L) for the (center) pile, with an L/D of 30 and at discrete values of K_{PS} for both foundation systems. They respectively relate to loading at vertical and horizontal directions.

The observed trend in aforementioned figures between the percentage of absorbed vertical and horizontal load at the top of the center pile, with K_{PS} variation (from 1000 to 10000), do agree with comments expressed on previous items respectively done for Figs. 8 and 15.

Nevertheless, one also notices from Figs. 16 and 17 that:

- For the horizontal direction, in any case, the distribution of load along the pile's length tends to be more "concentrated" (less homogeneous) on top positions of the shaft. This is especially noticeable for the top 50% of the pile (that means z/L up to around 0.5). Tension loads have also appeared on the remaining lower sections, denoting that a "neutral" point existed, where the top compressive loads turned into tension ones at the bottom;
- For the vertical direction, and also in any case, the distribution of the load is much more homogeneous along the depth;
- For the vertical direction, the magnitude of the load (in percentage to total) along the whole pile's length decreased with the increase of the pile-soil stiffness K_{PS}, whereas the opposite happens for the horizontal direction (in the aforementioned top region). In the latter case

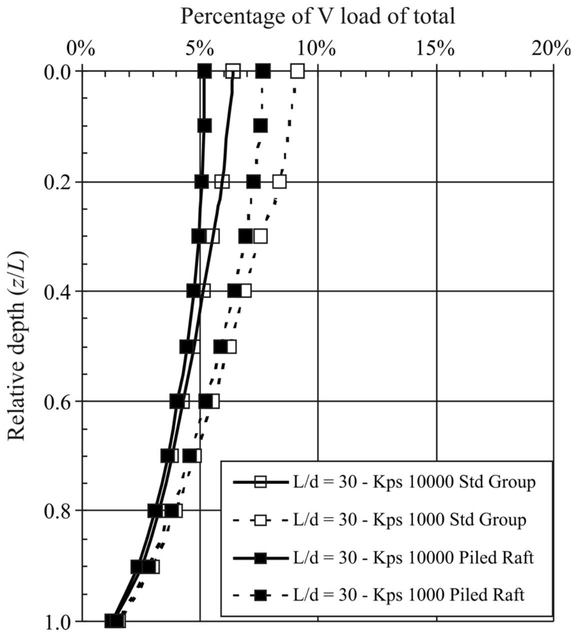

Figure 16 - Vertical load variation along (center) pile length at distinct conditions for both systems.

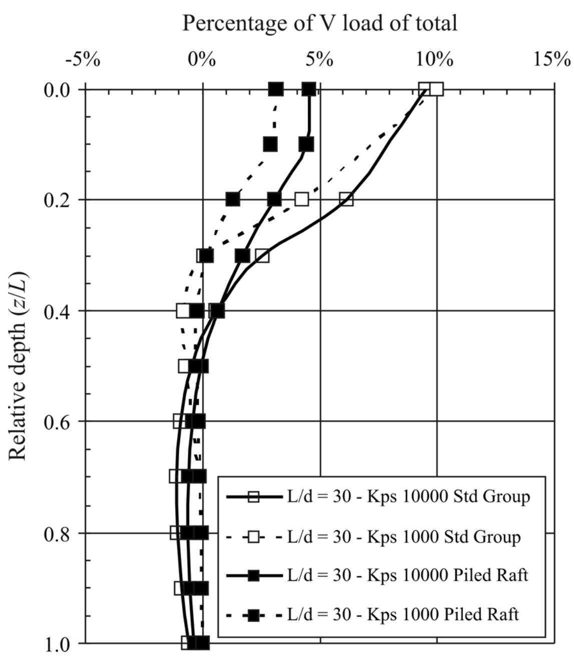

Figure 17 - Horizontal load variation along (center) pile length at distinct conditions for both systems.

the magnitude of the load along the pile's length increased with the increase of K_{PS}.

Such dissimilarities undoubtedly denote differences in the foundation behavior when loaded at distinct directions. Perhaps it could explain part of the differences observed on equivalent data when comparing it at each load direction. Nevertheless, more research is still needed to foster grounded conclusions in such behavioral aspect.

4. Conclusions

This paper investigated the individual behavior of piled rafts and standard pile groups with differing characteristics of relative stiffness (pile-soil, raft-soil), slenderness ratio (pile) and Poisson's Coeff. (soil), at both non simultaneous vertical and horizontal load conditions.

Although the range of the numerical parametric analyses was limited, generalized conclusions have been drawn. This knowledge can off course be referenced as an *initial* guideline in the design of similar foundation systems.

Therefore, based on aforementioned results and discussion, and bearing in mind the partial conclusions drawn in each sub item, it is possible to suggest that:

- Foundation systems can be designed (as usually done) as conventional groups if the main variable of interest is the vertical settlement (either total or differential). Nevertheless, the group should be preferably designed with a high slenderness ratio for the pile (longer piles as practically possible for a constant diameter), and high relative pile-soil (≥ 1000) and raft-soil (≥ 10) stiffnesses;
- Foundation systems must be designed (as it is not usual yet) as piled rafts if the main variable of interest is the horizontal displacement of the raft (total). It shall be preferably designed, again, with a high relative pile-soil (≥ 1000) and raft-soil (≥ 10) stiffness;
- If the system can not be designed as a piled raft, in the case of horizontal loading, it should at least have the same characteristics suggested at previous Item(1);
- Care should be taken in the structural reinforcement of the piles when adopting aforementioned suggestions, as by decreasing the pile compressibility there will be also a tendency of more non-uniform loads distributed within the system;
- In any case, the Poisson's Coefficient of the soil can be fixed without problems, as it seems to be not a parameter of strong influence on the final results;
- When designing the system as a piled raft, some sort of "rationalization" procedure, as advocated by some of the cited references of this paper, could be employed in order to enhance in design some of the (beneficial) features observed herein with the numerical analyses. Perhaps, for instance, by allowing center and lateral piles to have higher lengths than corner piles (although this possibility needs yet to be numerically better assessed). This feature is, nevertheless, already being implemented in the few piled raft projects of the city of Goiânia/Brazil (Sales 2013, personal communication).

Acknowledgments

This study was made possible through an existing joint technical co-operation research program from the Universities of Sydney in Australia and Brasília in Brazil, where students from both institutions were able to correspond and interact. In this regard, the authors are grateful to the kind support and comradeship provided by both (retired) Profs. H.G. Poulos and J.C. Small, and Dr. H. Zhang (SMEC Australia Pty Ltd.). The authors also thank the Brazilian sponsorship organizations CNPq and CAPES for all related support in this and in all other studies carried out by the GPFees Group, either in terms of personal research grants, or via sabbatical & student scholarships.

One of such scholarships allowed the MSc Student J.E. Bezerra to generate the raw data and illustrative plots used as basis of this paper. Although the paper considerably differs from the original knowledge generated by this particular Dissertation, as it expands and explores further its interpretation and conclusions, the authors are nevertheless indebted for the work done by Mr. Bezerra.

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