Evaluation of the influence of floor plan geometry of reinforced concrete buildings on the soil-structure interaction mechanism

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Abstract. This study aims to evaluate the effect of floor plan geometry of reinforced concrete buildings on the soil-structure interaction (SSI) mechanism. Two three-dimensional finite element models were developed using the SAP2000 software: (i) a model with a square floor plan and (ii) a model with a rectangular floor plan. Both fixed (rigid) supports and elastic (spring) supports were employed in the analyses to simulate foundation behavior. The results indicate that both models exhibit similar SSI responses, with noticeable redistribution of internal forces when interaction is considered. Peripheral columns experienced increased axial demands, while central columns showed a reduction. Additionally, there was an increase in positive bending moments at mid-spans and negative moments at the peripheral supports of the central ground floor beam. These findings highlight that neglecting settlement effects - by disregarding SSI in the design process - can result in bending moment diagrams that deviate from design assumptions, potentially leading to localized plastic hinges in beams. It is also noteworthy that the rectangular floor plan exhibited higher differential settlement values, making the influence of SSI even more significant in the structural and foundation design.

Keywords: floor plan geometry, reinforced concrete buildings, soil-structure interaction.

1 Introduction

The deformability of foundations can influence the distribution of loads in the superstructure. Therefore, the analysis of the soil-foundation-superstructure interaction must be considered when calculating the displacements and internal forces of the superstructure/infrastructure system. The analysis that takes these factors into account during the design stage is known as soil-structure interaction (SSI).

Studies on SSI generally show a transfer of loads from the supports that tend to settle more to those that settle less. It is observed that the external columns of buildings tend to experience an increase in loads, while the internal columns show a decrease. Moreover, SSI also affects the forces in tie beams and lower beams. The increase in forces in these elements (which are usually disregarded in simplified analyses) can pose a risk to the structure, depending on the magnitude of this increase. Gusmão [1] notes that both theoretical analyses and real-world case studies confirm the importance of SSI in building design, potentially leading to more economical and safer projects.

Aoki [2] and [3] proposed a simple model for the transfer of isolated vertical loads to the soil mass, and later extended it to the case of pile groups and pile caps interconnected by the superstructure. For the calculation of structures considering SSI, the following procedure was suggested: initially, the structural engineer calculates the loads on the columns, assuming the foundations are non-deformable. Based on these loads, the foundation engineer estimates the settlements, assuming the structure has zero stiffness, resulting in a settlement profile. The structural engineer then divides the loads by the settlements to obtain the initial spring coefficients at each column and recalculates the loads, now considering the structure supported by elastic supports. Based on these new loads, the foundation engineer recalculates the settlements, again assuming the structure has zero stiffness, obtaining a new settlement profile. The structural engineer re-evaluates the new spring coefficients from this updated settlement profile, recalculates the loads, and sends the information back to the geotechnical engineer. This is an iterative process, continuing until the desired convergence is achieved. This procedure is valid only for linear elastic soil behavior, which is a reasonable approximation only for sandy soils. In the case of clayey soils, the same procedure

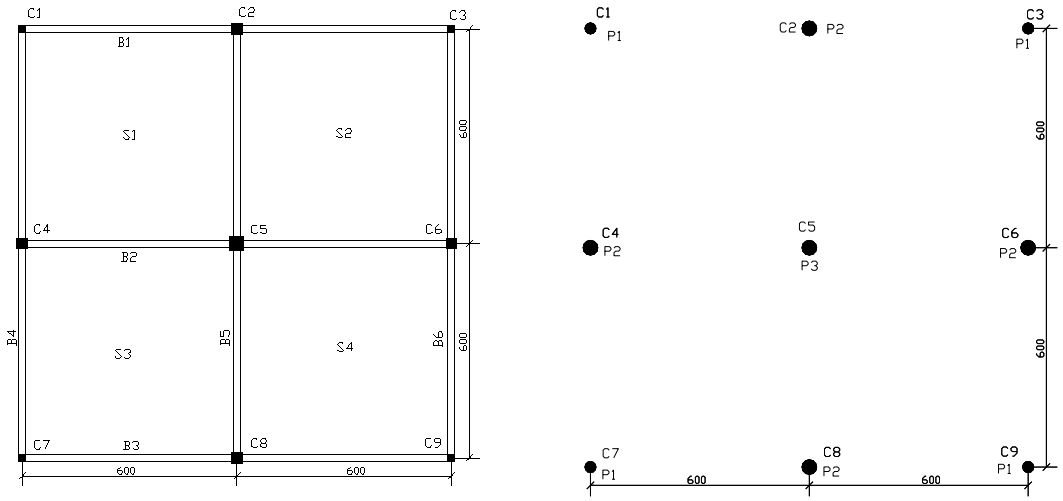
applies, but the settlement estimate must consider a soil model that accounts not only for the settlement value but also for its rate, which is related to the soil's consolidation coefficient.

Some influential factors in SSI include the relative stiffness between the structure and the soil, the construction sequence, the number of building floors, the presence of tie beams, the three-dimensional frame effect, and the building's plan shape.

In the present article, the effect of the building's plan shape is studied. For this purpose, two finite element models are developed using the commercial structural analysis software SAP2000 (version 15. This is the only licensed version currently available at the Department of Structures of the Federal University of Juiz de Fora. Despite being an older release, it enables the intended analyses to be carried out) [4]. The plan of the first three-dimensional model is square, while the second is rectangular. For the analyses, both fixed supports and elastic (spring) supports are used (the soil profile for both models is low-compaction sand). The stiffness coefficients for the spring supports are defined according to the proposal by Poulos and Davis [5].

2 Building and foundation characteristics

The buildings under study are reinforced concrete structures with four floors. The floor-to-ceiling height is uniform, at three meters. The buildings have double symmetry, and the plan of the first model (square plan) is shown in Fig. 1(a) and Fig. 1(b) illustrates the pile foundations with circular cross-sections (P1, P2, and P3, with diameters of 30, 40, and 60 centimeters, respectively).



(a) (b)

Figure 1. (a) Square floor plan of the building (dimensions in centimeters) and (b) pile foundations (dimensions in centimeters)

From Fig. 1(a), it can be observed that the building has 9 columns extending down to the foundations. Columns C1, C3, C7, and C9 have a cross-sectional area of 20 x 20 centimeters. Columns C2, C4, C6, and C8 have a cross-sectional area of 30 x 30 centimeters, and column C5 has a cross-sectional area of 40 x 40 centimeters. All beams have a cross-sectional area of 20 x 80 centimeters. The slabs have a thickness of 10 centimeters. Figure 2 shows the floor plan of the second model (rectangular plan).

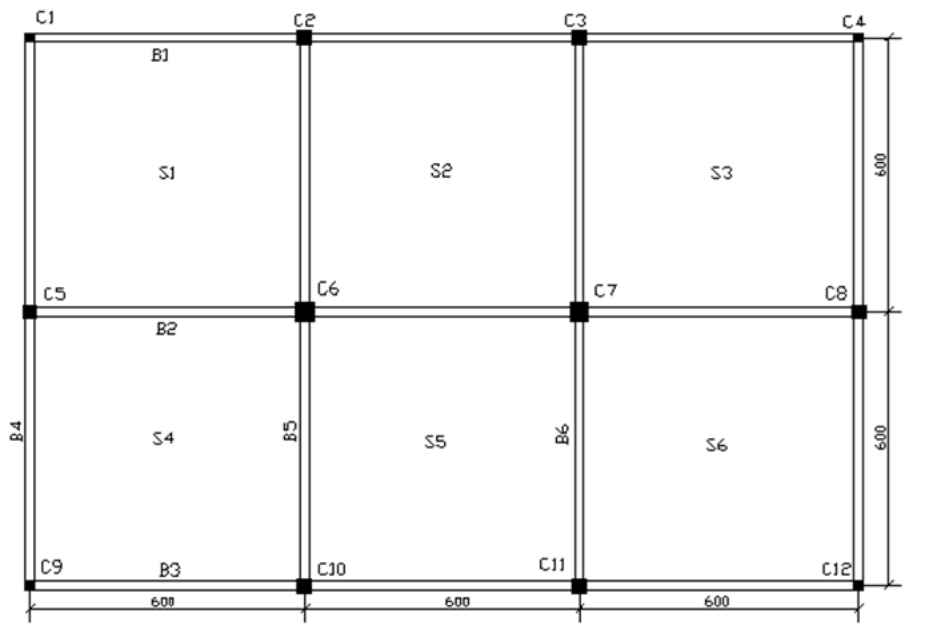


Figure 2. Rectangular floor plan of the building (dimensions in centimeters)

From Fig. 2, it can be seen that the building has 12 columns extending down to the foundations. Columns C1, C4, C9, and C12 have a cross-sectional area of 20 x 20 centimeters. Columns C2, C3, C5, C8, C10, and C11 have a cross-sectional area of 30 x 30 centimeters, while columns C6 and C7 have a cross-sectional area of 40 x 40 centimeters. All beams have a cross-section of 20 x 80 centimeters. The slabs have a thickness of 10 centimeters.

For both models—the square and the rectangular floor plan—the loads considered include the self-weight of the structure and an imposed load of 3 kN/m² on the slabs. The material properties of the superstructure (slabs, beams, and columns) are as follows: concrete compressive strength f_{ck} = 21 MPa, unit weight = 25 kN/m³, modulus of elasticity $E = 25700$ MPa, and Poisson's ratio = 0.2. The foundations consist of precast isolated concrete piles with diameters of 30, 40, and 60 centimeters, driven 14 meters deep into a thick layer of very low-compaction sand ($E = 9$ MPa and $\nu = 0{,}2$ – hypothetical values).

3 Computational modeling of the reinforced concrete buildings

The structures were discretized into finite elements using the commercial structural analysis software SAP2000 (Version 15) [4]. Beam and column elements were modeled using frame elements, while slab and masonry elements were modeled using shell elements.

Figure 3(a) shows the three-dimensional model with a square floor plan, and Fig. 3(b) shows the model with a rectangular floor plan.

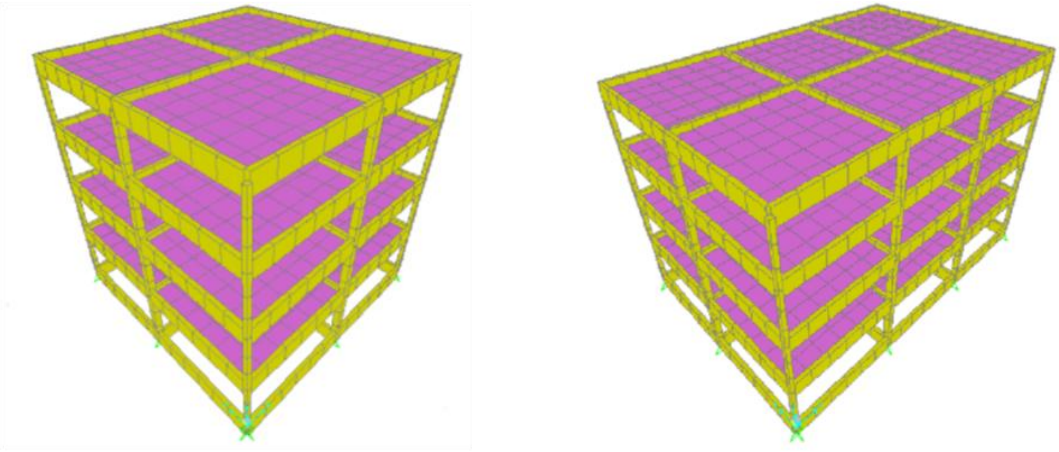
For the analyses, both fixed supports and spring supports are used. The stiffness coefficients of the supports (K) are defined using eq. 1:

$$K = \frac{Q}{w}\left(\frac{kN}{m}\right). \tag{1}$$

Where:

Q is the load (kN).

w is the estimated settlement for the piles based on Poulos and Davis [5].



(a) (b)

Figure 3. (a) Three-dimensional model of the building with a square floor plan and (b) model with a rectangular floor plan

4 Poulos and Davis model for pile settlement estimation

Poulos and Davis [5] introduced a rational method for estimating pile settlements based on numerical procedures that employ Mindlin's equations [6]. The method, presented in the form of charts, allows for the prediction of settlement of an individual pile, initially assumed to be incompressible, in a semi-infinite, homogeneous elastic medium. Subsequently, corrective factors were developed to account for the influence of pile compressibility, the presence of a considered rigid (or immovable) boundary, the Poisson's ratio, and soil improvement at the base level. For a pile with diameter or width B, embedded in a medium with Young's modulus E, loaded (in compression) by Q_0 at its top, the settlement at the top is given by eq. (2):

$$w_0 = \frac{Q_0 I}{EB}. \tag{2}$$

Equation (3) provides the most general influence factor (I), which incorporates different corrective factors.

$$I = I_0 R_k R_h R_v R_b. \tag{3}$$

Where:
I_0 is the influence factor for an incompressible pile in a homogeneous medium.
R_k is the factor considering pile compressibility.
R_h is the factor considering the presence of a rigid boundary below the pile tip.
R_v is the factor considering the Poisson coefficient.
R_b is the factor considering a stiffer soil below the pile base.

5 Results and discussions

Table 1 shows the corrective values used in the Poulos and Davis model (square floor plan of the building).

Table 1. Corrective factors in the Poulos and Davis model

Column	Pile diameter (m)	L/B	I0	Rk	Rv	I
C1	0,3	46,7	0,047	1,15	0,85	0,04594
C2	0,4	35,0	0,058	1,10	0,85	0,05423
C5	0,6	23,3	0,080	1,08	0,85	0,07344

Table 2 presents the axial force values obtained in the columns, both without considering soil-structure interaction and with interaction, for the structural model with a square floor plan. Table 3 presents the axial force values obtained in the columns, also with and without soil-structure interaction, for the model with a rectangular floor plan.

Table 2. Axial forces in the columns, without and with soil-structure interaction, for the model with a square floor plan

Column	Without interaction				With interaction		Difference (%)	
	Load (kN)	Settlement SD*	Settlement GD*	k = Q/w (kN/m)	Load (kN)	Settlement (mm)	Load	Settlement **
C1	207	0	3.50	59143	298	5.05	44	44
C2	593	0	8.90	66629	585	8.80	-1	-1
C5	1323	0	18.00	73500	994	13.50	-25	-25

* SD = initial structural design (without interaction); GD = initial geotechnical design (without interaction).

** Difference from the forecast in the initial geotechnical design (without interaction).

Table 3. Axial forces in the columns, without and with soil-structure interaction, for the model with a rectangular floor plan

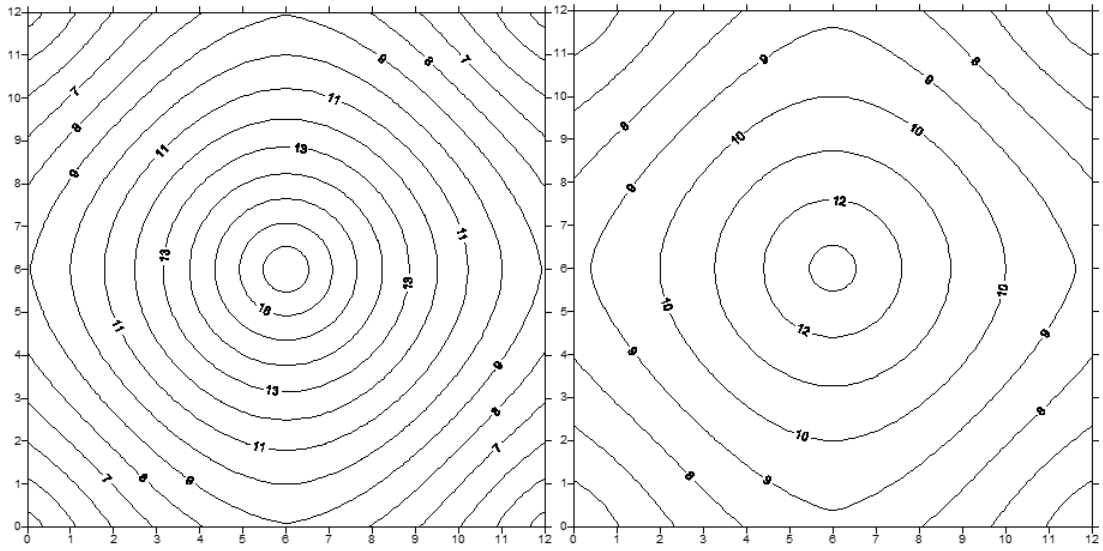
Column	Without interaction				With interaction		Difference (%)	
	Load (kN)	Settlement SD*	Settlement GD*	k = Q/w (kN/m)	Load (kN)	Settlement (mm)	Load	Settlement **
C1	212	0	3.61	58726	291	4.95	37	37
C2	540	0	8.13	66421	591	8.90	9	9
C5	600	0	9.04	66372	579	8.72	-4	-4
C6	1242	0	16.89	73535	1003	13.64	-19	-19

* SD = initial structural design (without interaction); GD = initial geotechnical design (without interaction).

** Difference from the forecast in the initial geotechnical design (without interaction).

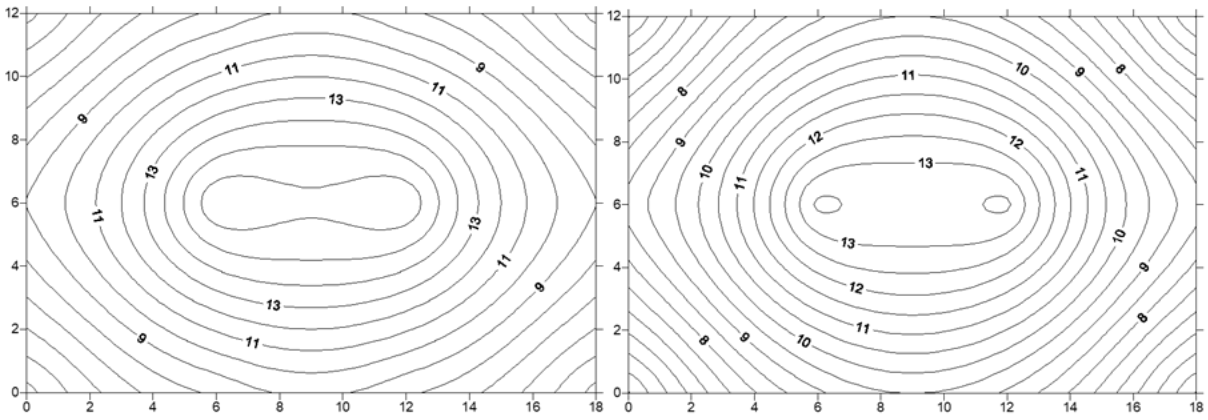
From Tab. 2 (model with a square floor plan), it is observed that in the second analysis, using deformable supports (with stiffness values *k*), new loads and settlements were produced (since the analysis is linear, the variations in loads and settlements are, naturally, proportional). The peripheral columns experienced an increase in load (a difference of 44%), while the central column had a decrease in load (a difference of 25%). In other words, as reported by Gusmão [1], a redistribution of forces among the columns occurred. A similar behavior is observed in Tab. 3, which presents the results for the model with a rectangular floor plan. An increase in load of approximately 37% was noted in the peripheral columns and a reduction of 19% in the central columns.

Figure 4 shows the settlement basin without considering soil-structure interaction and with interaction for the model with a square floor plan and the Fig. 5 illustrates the settlement basin without and with soil-structure interaction for the model with a rectangular floor plan.



(a) (b)

Figure 4. Settlement basin for the model with a square floor plan: (a) without considering soil-structure interaction and (b) with interaction



(a) (b)

Figure 5. Settlement basin for the model with a rectangular floor plan: (a) without considering soil-structure interaction and (b) with interaction

From Fig. 4 and Fig. 5, the effect of soil-structure interaction can be observed in the tendency for settlement uniformity. It is also evident that the model with a square floor plan shows a greater tendency toward uniform settlement compared to the model with a rectangular floor plan. In fact, Barata [7] emphasized that the closer the floor plan geometry is to a square, the greater the tendency for uniform settlement.

Figures 6 and 7 illustrate, respectively, the bending moment diagrams of the central lower beam (ground floor) for the square floor plan model and the rectangular floor plan model, for both analysis conditions – that is, without considering soil-structure interaction and with interaction. The central lower beam was selected because ground beams and tie beams are the most affected by settlements.

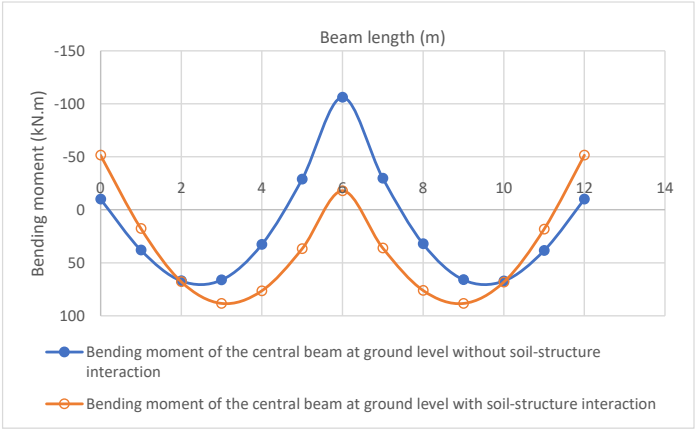


Figure 6. Bending moment diagram of the central ground floor beam, without and with soil-structure interaction, for the model with a square floor plan

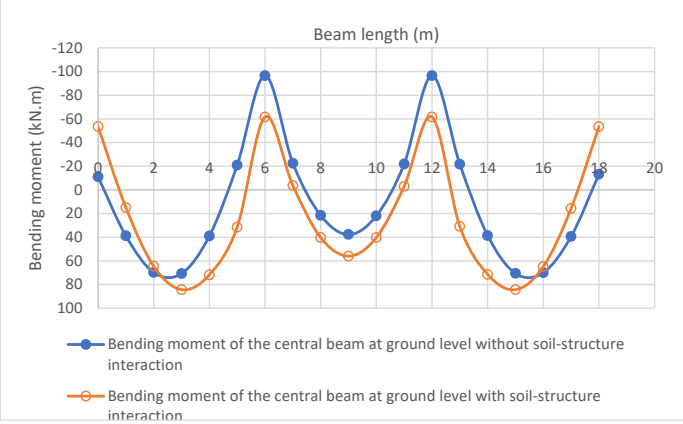


Figure 7. Bending moment diagram of the central beam at the ground floor level, without considering soil-structure interaction and with interaction for the rectangular floor plan model

From Fig. 6, an increase in positive moments in the spans is noted (approximately 25% difference), as well as a considerable increase in negative moments at the peripheral supports (approximately 80% difference). From Fig. 7, there is an observed increase in positive moments in the spans (approximately 33% in the central span) and also an increase in negative moments at the peripheral supports (around 80% difference). It is observed that, for both the square and rectangular floor plan geometries, there are changes in the demand values due to settlements. In practice, if the structural design does not account for settlements (i.e., a design without soil-structure interaction), the settlements, by producing a different bending moment diagram than expected, may lead to localized plastic plastic hinges in the beams. It is evident that in cases where settlements are significant, the effect of soil-structure interaction is important not only for the foundation design but also for the structure itself. There are reports of buildings in Santos that have undergone significant settlements, showing crushed peripheral columns and severe cracking in the beams at the lower levels.

6 Conclusions

The following conclusions are listed:

(i) The results for the square floor plan model are similar to those of the rectangular floor plan model. That is, when considering soil-structure interaction, a redistribution of internal forces in the structural elements was observed.

(ii) Peripheral columns showed increased loading, while central columns experienced load relief.

(iii) For both square and rectangular floor plan models, the redistribution of forces in peripheral columns was significant. In fact, differences between the cases with and without soil-structure interaction were always greater than 30%.

(iv) A greater tendency for uniformity in differential settlements was observed in the square floor plan model. In other words, the closer the building's floor plan is to a square, the greater the tendency for uniform settlement distribution.

(v) An increase in positive bending moments in the spans and in negative moments at the peripheral supports of the central beam at the ground floor level was observed. This means that if the structural design does not account for settlements (as in the case without soil-structure interaction), the settlements, by producing a bending moment diagram different from that anticipated, can lead to localized plastic hinges in the beams.

(vi) From the present study, the importance of computational models is evident for understanding the soil-structure interaction mechanism. Furthermore, in cases where settlements are significant, the effect of soil-structure interaction is relevant not only in the design of foundations but also in the design of the superstructure.

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References

[1] Aoki, N. (1989) Discussion to Session 14, Proceedings, *12th ICSMFE*, v. 5, pp. 2963-2966, Rio de Janeiro.
[2] Aoki, N. (1997) Aspectos geotécnicos da interação estrutura-maciço de solos, *XXVIII Jornadas Sul Americanas de Engenharia Estrutural*, vol. 1, pp. VII – XX, São Carlos.
[3] Gusmão, A.D. (1990) Estudo da Interação Solo-Estrutura e sua Influência em Recalques de Edificações. Tese de M.Sc., COPPE/UFRJ, Rio de Janeiro, RJ, Brasil.
[4] SAP 2000 (2015) CSI Analysis Reference Manual v.15.0. Computers and Structures Inc., California, USA, 415 p.
[5] Poulos, H.G. and Davis, E.H. (1980) *Pile Foundation Analysis and Design*. New York: Wiley.
[6] Mindlin, R.D. (1936) *Force at a Point in the Interior of a Semi-infinite Solid*. Physics, v. 7.
[7] Barata, F.E. (1986) Recalques de Edifícios sobre Fundações Diretas em Terrenos de Compressibilidade Rápida e com a Consideração da Rigidez da Estrutura. Tese de Concurso para Professor Titular do Departamento de Construção Civil, Escola de Engenharia da UFRJ, Rio de Janeiro, RJ, Brasil.