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A Numerical Study on the Impact of Soil-Structure Interaction on the Structural Response of a Reinforced Concrete Building

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Abstract. This research aimed to investigate the impact of Soil-Structure Interaction (SSI) on a reinforced concrete building with a deep foundation, located in the region of Grande Vitória, Espírito Santo, Brazil. To this end, a structural model was developed considering, firstly, a rigid support and, subsequently, through an iterative process, a flexible support, in order to analyze changes in load distributions and structural settlements. The TQS software was utilized to model and calculate the superstructure loads, while PLAXIS 3D was employed for soil modeling and settlement estimation. The convergence of the iterative process was achieved from the third iteration, presenting an approximate variation of 5.0%. At the conclusion of the analysis, a maximum load relief of 16.05% and an overload of 25.42% were observed, highlighting the significance of considering soil deformability during the structural design process.

Keywords: Soil-Structure Interaction; Settlement; Flexible Support; Structural Analysis; Structural Modeling.

1 Introduction

In recent years, the construction of tall buildings has become common in Brazil, requiring greater attention to the analysis of the superstructure and foundation of buildings due to the complexity of the loads applied. Traditionally, structural and geotechnical designs are carried out separately, considering that the superstructure is supported on an immovable surface (rigid support), which disregards the actual deformability of the soil (Silva *et al.* [1]). This simplification can lead to inaccurate results regarding settlement and structural safety. The Soil-Structure Interaction (SSI) hypothesis then emerges as a more realistic approach, integrating soil, foundation, and superstructure, allowing for the joint analysis of the mutual influences of these elements and contributing to safer, more economical, and sustainable solutions (Gusmão [2]). Considering soil-structure interaction leads to more uniform settlements and causes variation in column loads (Velloso and Lopes [3]) and, according to Figueiredo *et al.* [4], not considering SSI during project design leads to results that differ from the actual behavior of the soil and structure, since the loads acting on the soil cause plastic deformation (settlements), which modify the initial conditions of the structure.

The proposed study aims to analyze the influence of SSI on the distribution of vertical loads on columns and on the estimated settlement of a building's foundation, comparing the effects of rigid and flexible supports.

2 Soil-Structure Interaction (SSI)

The SSI involves analyzing structural components together with foundation elements and soil, taking into account possible deformations in the foundations and their effects on the structure; thus, the stiffness of the structure and foundation is taken into account when calculating displacements and stresses. Poulos [5] proposes a method that considers the superstructure, infrastructure, and soil as a single system, presenting a matrix formulation for calculating settlement. This formulation for SSI is given by the combination of two sets of equations, those governing soil-foundation analysis and those governing superstructure-foundation analysis. Using

this method to develop a simplified methodology for performing this SSI analysis, Gusmão [2] reached some conclusions regarding the tendency toward uniform settlement, which does not increase linearly with the number of floors, with the greatest contribution occurring in the first floors, and which is more likely to occur the more square the building's floor plan is.

The Brazilian standard for Foundation Design and Execution (ABNT NBR 6122:2022 [6]) made SSI analysis mandatory for the following cases: a) Structures with significant variable loads in relation to the total load, such as silos and reservoirs; b) Structures over 55.0 m high, measured from the ground floor to the roof slab of the last habitable floor; c) Structures with a height/width (smaller dimension) ratio greater than four; and d) Unconventional foundations and structures.

The SSI analysis can be performed using computational methods, adding springs representing the foundations to the structure model (Velloso and Lopes [3]), as can be seen in Fig. 1.

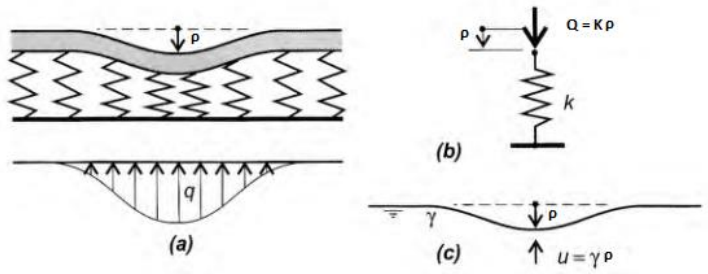


Figure 1. Winkler model

One of the hypotheses that makes this representation is the Winkler Hypothesis, which is based on considering that the loads are proportional to the soil settlements, demonstrating this typical spring behavior, as can be seen in eq. (1).

$$q = kv * \rho \tag{1}$$

Where kv a proportionality constant, called the vertical reaction coefficient, and ρ the estimated soil settlement.

Using this hypothesis, Silva and Sales [7] observed that there is a tendency in the variation of column loads when comparing rigid and flexible support depending on the type of column, such that peripheral columns tend to suffer overload and central columns tend to suffer relief, and foundations with greater soil settlement imply greater redistribution of loads on the columns, while Sousa *et al.* [8], when analyzing the effects of SSI on a building, observed that there was a pattern in the load migration process, relieving the initially more loaded columns and overloading the initially less loaded columns.

Bapir *et al.* [9] report that there is a consensus among researchers to ignore the effects of SSI for structures placed on very rigid soil and rock, whereas for structures supported on soft soil, the effects of SSI should be evaluated with an appropriate modeling technique, considering the nonlinear behavior of the soil. In addition, they point out that the effects of SSI have traditionally been considered beneficial and ignoring them can lead to an inadequate design.

3 Methodology

The study in question is based on a reinforced concrete building design with prestressed slabs located in Grande Vitória - ES, which is classified as mixed use, with shops and apartments. It consists of 26 floors, has a total height of approximately 90.0 meters, and a total built area of around 15.000 m². The tower's foundation design was developed using precast circular concrete piles with a diameter of 42.0 cm and a depth ranging from 7.5 m to 9.0 m.

In recent years, numerical modeling has become increasingly common in engineering project analysis. In this context, this building was modeled in CAD/TQS software, initially considering the support of the columns to be rigid. Permanent and accidental loads were applied to the structure in accordance with ABNT NBR 6120:2019

[10]. The modeling of the building can be seen in Fig. 2.

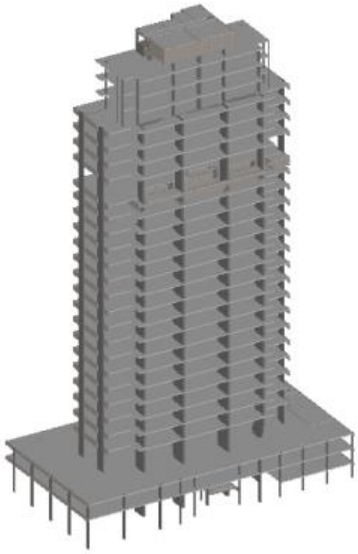
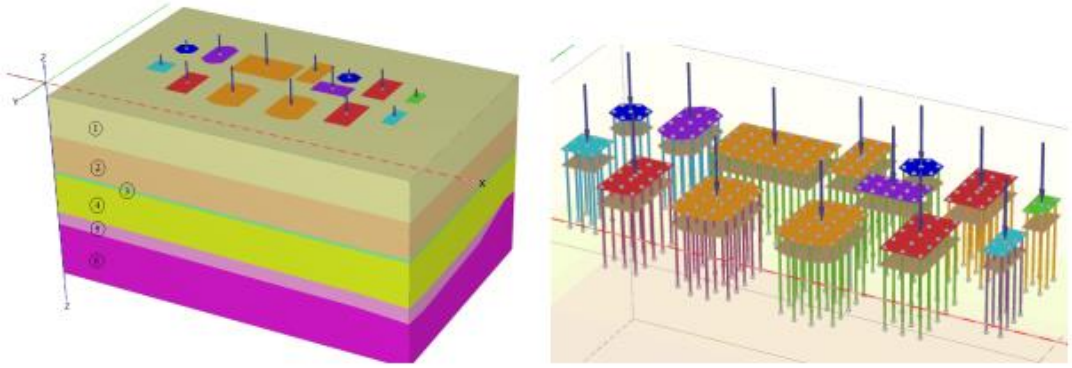


Figure 2. Building modeling

It should be noted that the entire building was modeled, tower and foundation, but only the tower columns will be analyzed in the study. After modeling considering rigid support, the model was duplicated and the consideration of rigid support was changed to flexible support, considering the deformability of the soil.

With the development of the finite element method, PLAXIS software has been used for some time by various authors, such as Zakia *et al.* [11] have conducted a finite element study in soil settlement predictions using PLAXIS 2D and Gowthaman and Nasvi [12] numerical simulation of load-settlement behavior of axially loaded pile group was simulated using PLAXIS 2D and PLAXIS 3D finite element packages.

To determine foundation soil settlements, the soil mass was modeled together with the foundation structure, piles, and blocks in PLAXIS 3D software, as shown in Fig. 3.



(a) Soil mass (b) Foundation elements

Figure 3. Modeling of the soil mass with the foundation in PLAXIS 3D

In PLAXIS 3D, three-dimensional modeling of the soil with the foundation structure is performed. The software is based on the finite element method for estimating soil settlement in foundations, considering the stiffness of the block as a function of its height and the contribution of the soil in the block's support projection (Lima [13]).

In the modeling, the Mohr-Coulomb model was used for the soil mass material, and the soil parameters for each layer were established through empirical correlations based on the survey data. The parameters used as input

data in the modeling were: layer thickness, average N_{SPT}, saturated specific weight (γ_{sat}), effective cohesion (c'), effective friction angle (ϕ'), modulus of elasticity (E), and Poisson's ratio (ν). The soil parameters can be seen in Table 1.

Table 1. Soil parameters

LAYER	SOIL	γ_{SAT} (kN/m³)	c' (kPa)	ϕ' (°)	E (kPa)	ν
1	Sand	20	3.0	35	24000	0.30
2	Cemented Sand	21	100.0	43	300000	0.30
3	Silty-Clayey Sand	19	10.0	30	35000	0.40
4	Medium and Fine Sand	21	3.0	40	135000	0.30
5	Clayey Sand	19	10.0	32	48000	0.35
6	Sandy Clay	19	12.0	27	30000	0.40

Chamecki [14] presented a methodology for analyzing SSI, taking into account the rigidity of the structure, in which foundation soil settlements are calculated based on the support reactions of the structure, initially considered immovable, and the load transfer coefficients. With these initial soil settlements, new reactions are calculated and, subsequently, new soil settlements. This process occurs iteratively until the reactions and soil settlements converge. Based on this methodology, the iterative process of the study in question is carried out by processing the building in CAD/TQS considering rigid supports. With the loads found, the soil settlements and spring coefficients are calculated in PLAXIS 3D. After that, the building is processed considering the deformability of the soil, including the spring coefficients. The variation in loads on the columns in these processes is compared. If convergence occurs, i.e., a variation of around 5.0%, the process is terminated. If convergence does not occur, the iterative process is repeated, calculating new soil settlements and defining new spring coefficients.

4 Results

Processing the computational models and following the methodology described above, convergence was found in the variation of loads in the order of 5.0% after three iterations. Table 2 shows the types of columns (peripheral and central) and the loads found in the processing of the building considering rigid and flexible supports, which were named ITE01, ITE02, and ITE03. Silva and Sales [7] observed a trend in changes in columns loads when comparing the model with rigid supports and flexible supports. This variation, which can be either an increase or a decrease, is linked to the column type, with peripheral column tending to increase the load (overload) and central column tending to decrease it (relief).

Table 2. Vertical loads on columns

COLUMNS	TYPE	RIGID SUPPORT (kN)	ITE 01 (kN)	ITE 02 (kN)	ITE 03 (kN)
P1	PERIPHERAL	6070	6490	6580	6600
P2	CENTRAL	14830	14640	14560	14530
P3	CENTRAL	13060	13050	13160	13210
P4	PERIPHERAL	4760	5230	5670	5970
P5	CENTRAL	14400	14370	14330	14310
P6	PERIPHERAL	5590	5980	6000	5980
P7	CENTRAL	25330	25180	25180	25160
P8	CENTRAL	16260	14700	14040	13650
P9	PERIPHERAL	8490	8570	8520	8510
P10	PERIPHERAL	8010	8250	8270	8290
P11	CENTRAL	15440	15430	15450	15460
P12	CENTRAL	20270	20030	20050	20060
P13	CENTRAL	20290	19980	20040	20080
P14	CENTRAL	15450	15450	15500	15530

The central columns P7, P12, and P13 had the highest loads in the structure, reaching values close to 25000 kN (P7) and 20000 kN (P12 and P13), while the peripheral columns P4 and P6 had the lowest loads in the structure, around 5000 kN. When analyzing the variations in vertical loads, which can be seen in Fig. 4, it can be observed that all peripheral columns had positive load variations, i.e., they were overloaded. This finding was also observed in the study by Silva and Sales [7]. Column P4 stands out, with a load variation from 4760 kN to 5970 kN, the largest variation being 25.42%. In most of the central column, however, the loads decreased, indicating relief, especially in P8, which had a load reduction of 16.05%, from 16260 kN to 13650 kN. In some central columns, such as P3, P11, and P12, there was a small increase in load when considering the SSI (about 0.6%). It is also interesting to note that the column that initially had the least load, P4, was the one that received the most overload. On the other hand, column P8, which is close to P4, was the one that had the most relief in load.

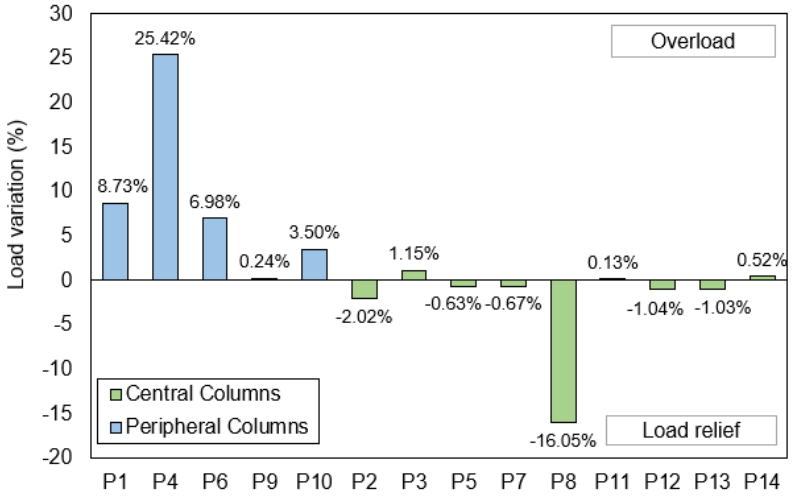


Figure 4. Variation in the vertical load on the columns

Figure 5 shows the columns that were overloaded and those that were relieved.

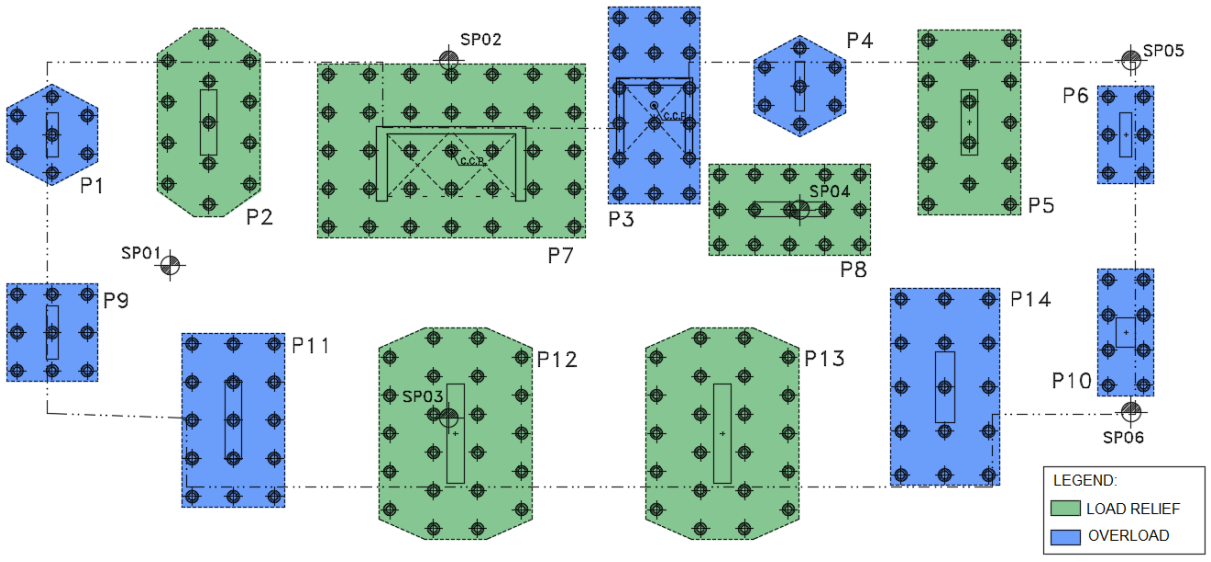


Figure 5. Plan showing variation in the vertical load on the columns

Table 3 shows the soil settlements calculated during the iterative process. It can be seen that the peripheral columns had the lowest soil settlements and the central columns had the highest soil settlements.

Table 3. Soil settlements

COLUMNS	TYPE	RIGID SUPPORT (cm)	ITE 01 (cm)	ITE 02 (cm)
P1	PERIPHERAL	2.27	2.34	2.36
P2	CENTRAL	3.15	3.13	3.12
P3	CENTRAL	3.74	3.70	3.70
P4	PERIPHERAL	3.42	3.43	3.48
P5	CENTRAL	3.25	3.23	3.23
P6	PERIPHERAL	2.35	2.42	2.43
P7	CENTRAL	3.57	3.53	3.53
P8	CENTRAL	4.31	4.14	4.09
P9	PERIPHERAL	2.44	2.46	2.45
P10	PERIPHERAL	2.52	2.55	2.55
P11	CENTRAL	3.12	3.11	3.11
P12	CENTRAL	3.51	3.47	3.47
P13	CENTRAL	3.61	3.54	3.54
P14	CENTRAL	3.26	3.23	3.23

Gonçalves [15] points out that, with the consideration of SSI, there is a transfer of load from supports that tend to settle more to those that tend to settle less, and this was found in the central column P8. This column presented the highest soil settlement values in the stages of the iterative process, due to the fact that it is located in the region with the most deformable soil mass on the site. As a result, it transferred load to nearby columns and, consequently, reduced its load.

Figure 6 shows the variations in soil settlement found at the end of the iterative process, comparing rigid support with flexible support (ITE 02). It can be seen that all peripheral columns experienced an increase in soil settlement, while the central columns experienced a reduction. It should be noted that columns P1 and P6 experienced the greatest increases in soil settlement, 3.96% and 3.40%, respectively, while column P8 experienced the greatest relief, 5.10%.

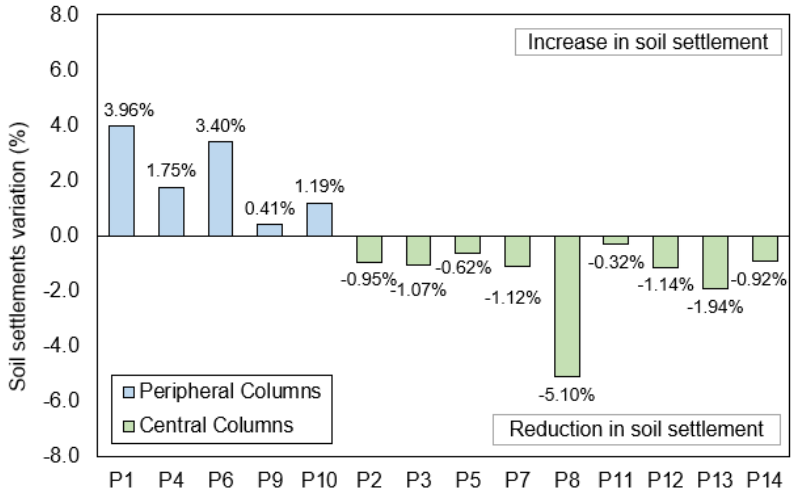


Figure 6. Variation in calculated soil settlements

The peripheral columns are less loaded than the central ones, which leads them to have lower soil settlements in the initial situation. When considering the SSI, the columns with lower soil settlements absorb loads from columns with higher soil settlements, which leads to an increase in the soil settlement value. The opposite occurs with the central columns, which have higher soil settlements.

5 Conclusions

The analysis clearly demonstrated the importance of considering Soil-Structure Interaction (SSI) in

reinforced concrete buildings with deep foundations. The comparison between rigid and flexible support models revealed that soil deformability significantly influences the redistribution of vertical loads and the soil settlements of the foundations. It was observed that the peripheral columns exhibited an increase in load, while the central columns showed a load reduction, highlighting the tendency of load migration from more heavily loaded elements to less loaded ones when soil flexibility is taken into account. Furthermore, the soil settlements obtained through three-dimensional modeling using the PLAXIS 3D software showed significant variations due to SSI: the peripheral columns presented increased soil settlements, whereas the central ones exhibited reductions. The results reinforce the importance of including SSI in the structural design process, especially in tall buildings and in regions with variable soil stiffness, since adopting more realistic models allows for a better prediction of the overall structural behavior, improving project safety and efficiency. Therefore, it is concluded that the consideration of SSI should not be neglected, as it is essential to ensure a more accurate, economical, and norm-compliant design.

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