# Understanding the Mechanism of Static Soil-Structure Interaction - A Case Study

G. Savaris, P.H. Hallak, P.C.A. Maia

**Abstract.** During the construction of a building, a transfer of loads occurs from the columns which tend to settle more to those that tend to settle less. This observable fact can be attributed to the mechanism called static soil-structure interaction (SSI). In order to understand this mechanism, which is often not considered in designs, an experimental campaign and a numerical simulation were carried out on a building which had its settlements monitored from the start of its construction. For this purpose, linear tridimensional numerical models were constructed for each floor and numerical analysis was performed, using the finite elements method. In this analysis, numerical models corresponding to the execution of each floor were used, considering the settlements measured at each stage of the construction. Results show a change in reaction forces which occurs when settlements are introduced into the model. It was also possible to verify that the spring coefficients of the foundations change along the ground surface, which suggests that they are related to the structural stiffness and with the foundation adopted. Furthermore, the analysis of the susceptibility of the structure to settlements presents results which could justify a greater influence of settlements during the first stages of the construction, with lower stiffness of the structure associated with greater load variation in columns.

**Keywords:** FEM analysis, static soil-structure interaction, settlements, soil-foundation spring coefficient, structural stiffness.

## 1. Introduction

Traditionally, building projects have been drawn up presuming that the supports on the ground are non-displaceable, resulting in a set of loads (vertical, horizontal reactions and flexural moments) which are passed to the foundation engineer who, considering the results obtained in the field trials, designs the foundations.

In reality, the performance of a building is governed by the interaction between the superstructure, infrastructure and foundation soil, in a mechanism denominated static soil-structure interaction (SSI). Through this mechanism, during the construction of a building, a transfer of loads occurs from the columns which tend to settle more to those that tend to settle less. Load transfer between the columns causes a trend towards uniformity of settlements, resulting in smaller displacements than those estimated. This effect may be found when settlements of foundations are monitored during construction, and throughout the lifetime of the building.

Nonetheless, monitoring building during construction, observing the behaviour of the foundations as they are being loaded, in addition to serving as a certification of quality of the projects and execution of the construction, is also a great contribution to the study of the mechanism of interaction between the structure and the soil.

Following this trend of monitoring buildings during their construction, this work intends to present the results obtained with the numerical analysis of a construction which had its settlements monitored from the beginning. Actually, the main focus is concentrated on observing the interaction between the structure and the foundations, by measuring their displacements during the construction of the building. The effects of this mechanism is analysed as regards certain important aspects such as the load variation in columns, the spring foundation coefficients and the stiffness of the structure.

Furthermore, this work contributes to the formation of a database about the static SSI and makes this mechanism an important tool that should not be underestimated or misunderstood in building design. Through this study, we expect to help future research into the development of methodologies for analysing the soil-structure interaction in building projects.

In the next section the mechanism of the soil-structure interaction and its observed consequences in a number of cases are presented. After that, a review of some models found in the literature is presented as well as the description of the building. Finally, the results and conclusions are presented.

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## 2. Static Soil-Structure Interaction (SSI) Mechanism

The static soil-structure interaction mechanism can be observed, for example, by the static analysis of a system composed of a beam supported by three columns, subjected to a uniformly distributed load, as presented in Fig. 1(a). In this case, the load acting on the central column, determined by conventional static analysis, corresponds to twice the load on the lateral columns. Due to the higher load, the foundation of the central column tends to suffer greater displacements; however, depending on the magnitude of the beam rigidity, this displacement is restricted, causing transfer of loads to the lateral columns. Consequently, the displacement of the central column is less than expected, while the displacement of the lateral columns will be greater.

In addition to the effects of rigidity of the structure on the foundation displacements, these displacements will also influence the deformation of the structure. This can be observed when we compare the deformation of elements of the structure in Fig. 1. In a linear analysis we observe that the final conditions of deformation of a structure consist of the sum of the deformations of the elements, due to the loads and redistributions, and they can be obtained only by an interactive analysis of the soil-foundation-structure system.

Thus, the study of settlements may be used as a tool for the analysis of the static soil-structure interaction mechanisms. For this purpose, an initial prediction of the settlements is made, considering the isolated foundations, and the settlements of the building are monitored during its construction and over its lifetime.

The performance of any building can be evaluated by means of two models of analysis: in the first model (Fig. 2(a)) the foundations are designed and the settlements estimated considering only the loading coming from the structure and in the second model (Fig. 2(b)) the stiffness of the structure is considered in the estimate of settlements. It can be verified that the deformation of settlements becomes smaller due to the influence of the interaction of the soil and structure, with the central supports tending to settle less than predicted and the peripheral supports settling more.

The impediment of settlements caused by the rigidity of the structure alters the maximum and minimum settlements, and consequently the differential settlements. Nevertheless, the total mean estimated settlements do not alter

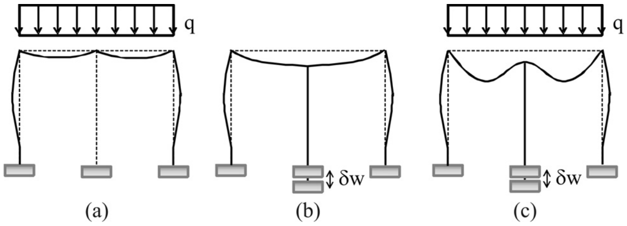


**Figure 1** - Soil-structure interaction model.

significantly. Thus, the angular distortions caused by the differential settlements are minimized, making it feasible to use foundations solutions that would not be possible to achieve by conventional studies (Gusmão & Calado, 2002).

The redistribution of forces on elements of the structure is a consequence of greater uniformity of the settlements. According to Goshy (1978), this occurs with greater intensity on the lower floors of buildings, where the open framed structure with panels behaves in the same way as vertical planes, similarly to a deep beam. Thus, the lower parts of the structure are more susceptible to flexural deformations, as shown in Fig. 3.

According to Gusmão & Calado Jr. (2002), the variation in the flexural moments, and torsional and cutting forces, are negligible, in comparison with the axial forces. Redistribution of load on the columns generates the transfer of load from the supports that tend to settle more to those that tend to settle less. These increases in load are signifi-

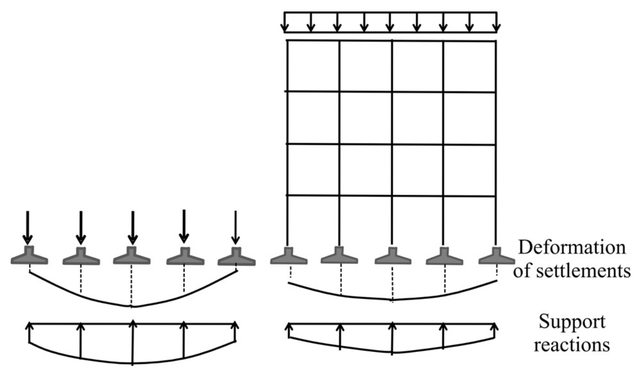


**Figure 2** - Effect of SSI on settlements and support reactions (adapted from Gusmão (1994)).

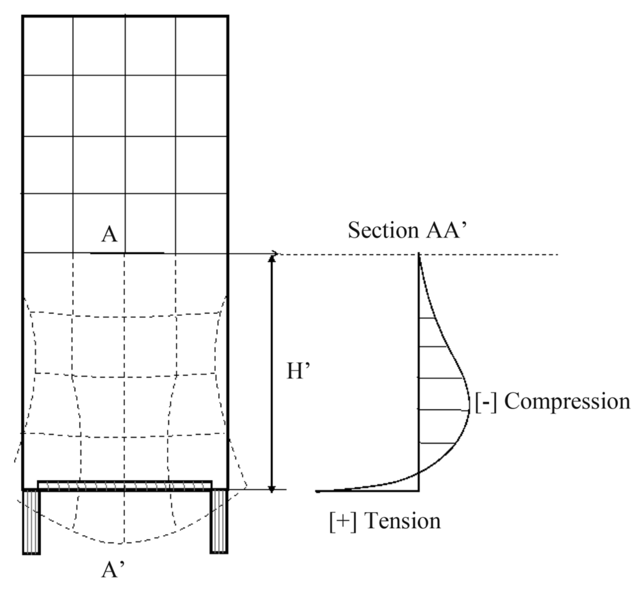


**Figure 3** - Analogy with the Deep Beam (H' → is the influence height).

cant, and can attain variations of up to 30% in the load foreseen in the rigid model (Gusmão (2006) and Gusmão & Calado Jr. (2002)). These increases in loads can cause pathologies in the structural elements, such as cracking of beams and concrete slabs, and crushing of columns.

Determining the loads acting on the columns of buildings has been performed in two ways: by measuring the deformation of the columns, using defined concepts of strength of material for load determination, or by estimation or measurement of settlements, using computer programs for structural analysis, in which the settlements measured are applied as prescribed displacements on the supports.

In modelling the structure, some simplifications are generally made, directly related to the consequences on the final product built. Some of these simplified hypotheses and their respective consequences have been reported by Gusmão (1994) and are presented in Table 1. Thus, we observe the need for considering the interaction between the soil and the structure in designing buildings, with the goal, above all, of minimizing pathologies.

## 3. Proposed Models for the Static SSI Evaluation

A review of the main methods for static soil structure analysis is presented in Table 2. It should be noted that all methodologies aim to simplify the problem by transforming the superstructure into an equivalent stiffness element. A more rigorous method allows for the superstructure and the foundation working together as a whole body.

All methodologies have some limitations as regards their numerical performance and the available computational capacity. Moreover, all methods are based on the elasticity theory, which can narrow their applicability for cases with large deformation of the superstructure or the foundation.

It is important to note that, in these methodologies, the calculation of settlements is usually done using theoretical models based on the literature. However, optionally, one can use settlements measured *in situ*, which allow a better definition of the spring foundation coefficient. This was the option adopted in the present work, in accordance with the methodology proposed by Iwamoto (2000) and Crespo (2004).

Illustrations of each model are as follows: Fig. 4 shows the equivalent beam proposed by Meyerhof (1953); Fig. 5(a) is a representation of the model proposed by Chamecki (1954) and used by Poulos (1975), Iwamoto (2000) and Crespo (2004); Fig. 5(b) is a representation of the model adopted by Colares (2006) and Mota *et al.* (2007); and, finally, Fig. 5(c) is the model adopted by Almeida (2003) and Ribeiro (2005)

The methodology adopted in this work uses the finite element method of a discretised building in order to investigate its structural behaviour. The numerical model does not consider the foundation and soil directly, but by introducing the measured settlements of all columns and for each stage of construction. This procedure is similar to that adopted by Gonçalves (2004) and Gonçalves *et al.* (2007).

## 4. Description of the Building Analysed and Computational Modelling

The study was carried out in a residential building, called Edifício Classic, located in the city of Campos dos Goytacazes - RJ, Brazil. In Fig. 6 a photo of the building is presented, in the final stages. Following the trend towards verticalization of buildings in the city, this building has 12 floors, constructed above the surface of the ground. The ground level has a social entrance and the garages, which are also extended to the following two floors. After this, there are nine floors with four residential units each, and the top-floor apartment, with a party area, machinery rooms and elevated reservoir.

**Table 1** - Consequences of the hypotheses of projects with regard to SSI (Gusmão, 1994).

| Calculation hypotheses | Consequence |
|---|---|
| Supports considered fixed | Redistribution of loads and forces on structural elements, especially beams and columns.<br>Load relief on most loaded columns and overload on less loaded columns.<br>There may be damage to structural elements. |
| Supports may settle in a manner independent of one another | The connection between structural elements gives the structure a rigidity that restricts differential settlements.<br>The measured deformation of settlements is less than that conventionally estimated.<br>There is a tendency towards uniformity of settlements. |
| The loading of the building only occurs at the end of construction | As the structure is being constructed there will be an increase in its load and in the absolute settlements.<br>There is, however, an increase in the rigidity of the structure, which causes a trend towards uniformization of the settlements.<br>There is a limit height, corresponding to the first five floors, beyond which there is practically no further increase in rigidity for the purposes of uniformity of settlements. |

**Table 2** - Methodologies normally used for static soil structure analysis (adapted from Aoki & Cintra (2004) and Savaris (2008)).

| Model | Meyerhof (1953) | Iwamoto (2000); Crespo (2004); Chamecki (1954); Poulos (1975) | Colares (2006); Mota *et al.* (2007) | Almeida (2003); Ribeiro (2005) |
|---|---|---|---|---|
| Model conception | The structure is replaced by a beam with equivalent stiffness | The superstructure and the foundation are considered as a separated body in balance. The elements of the foundation are considered as part of the fixed soil mass | The superstructure and the foundation are isolated and in equilibrium The foundation elements is part of the superstructure | It is considered as a single body in balance. The global system is formed by the structure and the mass of soil and the edge is limited by the fixed soil mass |
| Type of method for the solution to the problem | Analytical method | Displacement method | Finite element method | Finite element method and/or boundary method |
| Methodology for computing the stiffness of the structure | The stiffness of the equivalent beam is equal to the sum of the flexural stiffness of bars which compose the building and the masonry panel | The equivalent stiffness is determined as the force necessary to displace a point of the top surface of the foundation in one unit of length | The equivalent stiffness in each support is determined by dividing each reaction of the structure by its respective settlements | Numerically determined |
| Disadvantage | Large quantity of numerical operations and simplified computation of the stiffness of the structure | Each combination for one foundation element with one type of soil presents a different equivalent stiffness value | | Large quantity of data associated with high number of numerical operations |

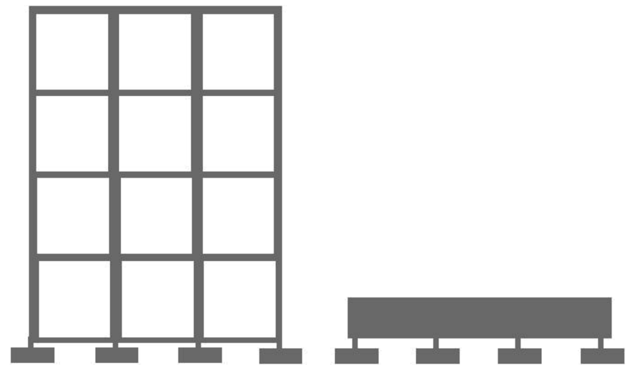


**Figure 4** - Beam with equivalent stiffness proposed by Meyerhof (1953).

### 4.1. Features of the Structure and of the Monitoring System

The building structure is formed by columns, board beams, ramps and stairs of conventional reinforced concrete, smooth concrete decks and two prestressed reinforced concrete transition beams, using a non-adherent prestressed system with greased single cables. The building has 35 columns in the first three floors, starting with the foundations, and for each floor 18 columns follow, with the transition of three columns occurring on prestressed beams. Closure of the building and internal divisions was done with brickwork using ceramic bricks with holes, and for closing the stairs, concrete blocks were used.

Figure 7 shows important details of the position of the foundations and the numbering of the columns. The columns in the central region (columns 1 to 20) have deep foundations and continue along the typical floor, whereas the columns in the external region (columns 21 to 37) are supported on footing foundation and end on the $2^{nd}$ or $3^{rd}$ floor. Also in Fig. 7 it is possible to see the foundation loads obtained by conventional design, which means considering fixed supports, range between 300 kN and 5200 kN.

The footing foundation is seated at 1.80 m from the surface of the ground, on a compacted layer of soil, improved by the mixture of sand and cement. The piles were made by continuously monitored helical equipment, 400 mm in diameter, and a mean depth of 12.5 m, reinforced in the first three metres.

In Fig. 7 it is also possible to see the network of the hydraulic system for monitoring the settlements of all columns, which is based on the communicant pipe principle, similar to the Terzaghi system. In this work, interconnected silicon pipes, with water outlets in the base of all columns and in the reference mark, were adopted. This scheme made it possible to observe the level of water in all columns and in the reference mark simultaneously.

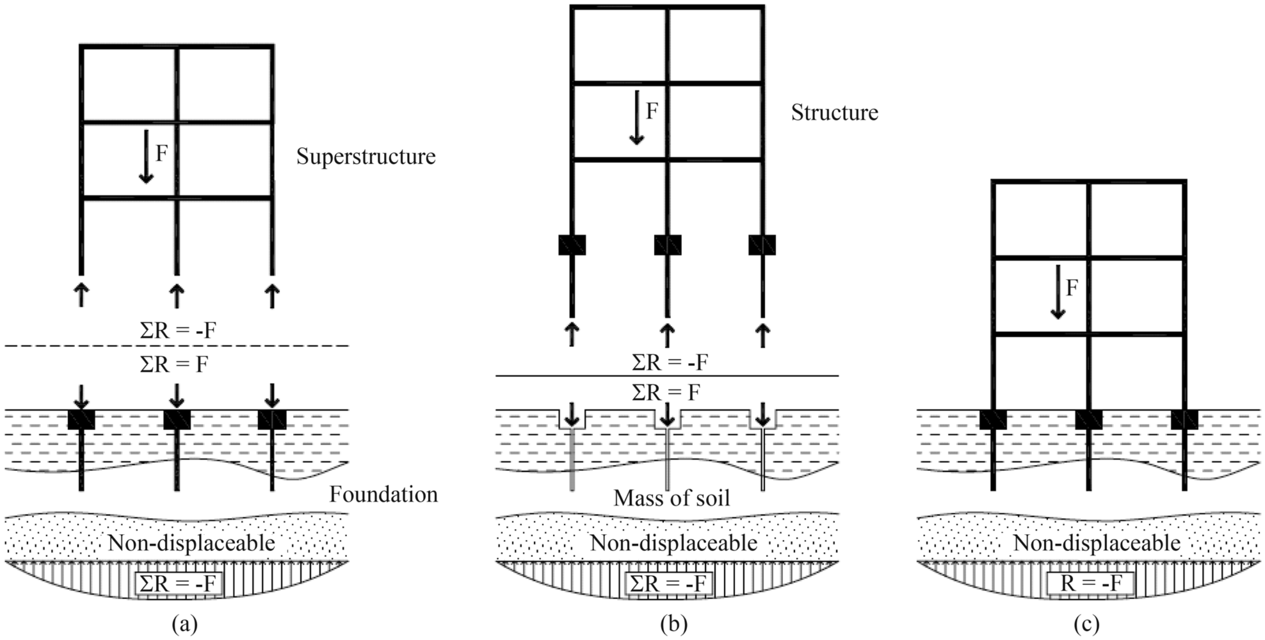


**Figure 5** - Models for soil-structure interaction analysis (adapted from Mota *et al.*, 2007).

**Figure 6** - Front Elevation of Edifício Classic.

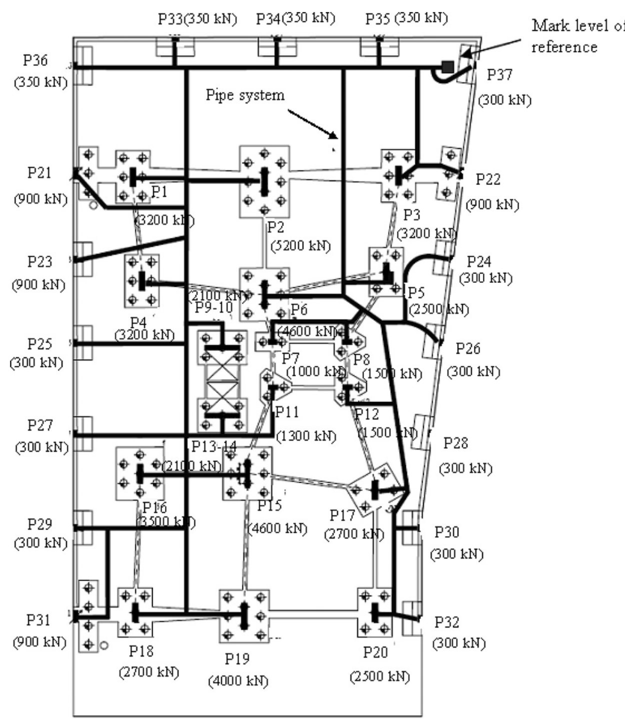


**Figure 7** - Sketches of the foundations, location of columns with respective design loads, level reference mark, pipe network and project loads.

The reference mark level was installed in a region that did not suffer any influence from the foundation elements. It was made up of a deep foundation with 10 m of length to which a graduated calibrated metallic bar was coupled. On the edge of the tubulation network, located on each column and on the reference mark, glass tubes were installed. On the reference mark the glass tube was fixed on the lateral of the graduated bar. The position of the level of water in relation to the top of the reference mark level was determined by the distance of the meniscus to the graduation of the metallic bar, as shown in Fig. 8.

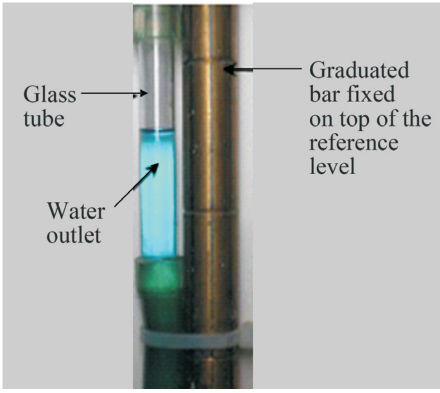


**Figure 8** - Metal post and water outlet on the reference mark.

On columns, the glass tube was fixed on their reference level. The position of the reference level in relation to the reference level in the column is determined by the distance from the meniscus to the orifice of the metallic bars.

To circumvent the difficulties of reading the water levels and ensure greater accuracy, a digital process was adopted as a tool for determining the position of the meniscus. After obtaining a photograph of the meniscus in the field, the image was treated and examined in the laboratory using an image manipulation program.

Although we give only this short explanation about the monitoring system, readers are invited to consult the original dissertation of Savaris (2008) should they wish to obtain more details about the settlement measuring system used in the study.

## 4.2. Modelling of the structure

The Edifício Classic structure was modelled as finite elements, allowing a static numerical and linear analysis to be made, using a computer program for structural analysis. The beams and columns were modelled as uniaxial bar elements, defined by two nodes located on the line that passes through the centre of gravity of the section. These elements have tension, compression, torsion and flexural capacities. The elements have six degrees of freedom in each node, three being rotations and three translations. On the columns, the eccentricities of the beams were disregarded, except for the columns of the lift shaft, in which rigid bar elements were inserted. These rigid bars transfer the load from the beams directly onto the axes of the columns.

The concrete slabs were considered as plate elements, defined by four nodes, with six degrees of freedom in each node, three being rotations and three translations. These were discretised in quadrangular elements according to the tracing of the prestressing cables.

The structural analysis took into consideration the construction process of the building through the development of twelve tridimensional models, corresponding to the execution of each of the concrete slabs of the building. Only the stages of construction in which the settlements of all the columns were monitored were considered.

As the measurements of the settlements had been made at points located at the bottom extremity of the ground floor columns, the tridimensional models did not take into consideration the elements of foundation and soil. In fact, this information was introduced by means of measured settlements.

By follow-up of the construction schedule, data was obtained on the execution of the brickwork on each floor, presented in Table 3, with the loads being entered because of the brickwork in the models with reference to the respective stages of the construction process. The wall was considered to have a thickness of 12 cm for the internal divi-

**Table 3** - Important construction data.

| Model | Date | Time of construction (days) | Stage of construction |
|---|---|---|---|
| I | 15/08/2005 | 0 | Execution of slab 1 |
| II | 22/09/2005 | 37 | Execution of slab 2 |
| III | 27/10/2005 | 73 | Execution of slab 3 |
| IV | 25/11/2005 | 101 | Execution of slab 4 and masonry on slab 1 |
| V | 14/12/2005 | 120 | Execution of slab 5 |
| VI | 29/12/2005 | 135 | Execution of slab 6 |
| VII | 14/01/2006 | 151 | Execution of slab 7 and masonry on slab 2 |
| VIII | 31/01/2006 | 167 | Execution of slab 8 and masonry on slab 3 |
| IX | 17/02/2006 | 184 | Execution of slab 9 and masonry on slab 4 |
| X | 16/03/2006 | 211 | Execution of slab 10 and masonry on slab 5 |
| XI | 15/04/2006 | 240 | Execution of slab 11 and masonry on slab 6 |
| XII | 17/07/2006 | 331 | Execution of slab 12 and masonry on slab 7 |
| XIII* | 04/10/2006 | 413 | Completed structure and masonry on slab 10 |
| XIV* | 02/07/2007 | 681 | Final stage of the construction. |

*For these stages there is no numerical model.

sions executed with ceramic bricks, and 15 cm for the stair walls, constructed with mortar blocks.

The weight of the structure itself was automatically calculated by the computer program from the dimensions of the elements and the physical properties of the materials. The accidental loadings were disregarded in the analyses. The specifications of the materials used in the construction were obtained from the architectural and structural projects, and, occasionally for the materials with non-specified properties, the recommendations in the Brazilian Standards NBR 6118 (ABNT, 2003) and NBR 6120 (ABNT, 1980) were adopted, as presented in Table 4. In this table fck is the characteristic compressive resistance of the concrete, fptk is the characteristic tension of rupture to traction of the pre-stressed steel and fpyk is the characteristic leakage resistance of the prestressed steel.

The prestressing performed in the concrete slabs and transition beams was considered as a set of Equivalent Concentrated Loads, as presented by Menegatti (2004). This methodology was proposed for considering prestressing in prestressed concrete elements. It aims to contribute to the optimization of the task of modelling the structure, due to the simplicity of obtaining the forces and the ease of application in commercial programs for structural analysis.

## 5. Performance of the Structure and the Influence of Settlements on the Analysis

This work intends to understand the mechanism of the interaction between the structure under construction and the foundation, referred to here as the static SSI mechanism. This mechanism represents the static action and reaction between both parts of a building, considering the experimental settlements obtained for each stage of construction. To accomplish this, a study about the variation of loads on the supports during the time of construction is first presented. Next, following certain tendencies which use spring coefficients in order to represent the soil reaction in the structures, we present an analysis of this parameter over the time of construction. Finally, an analysis of the influence of the stiffness of the structure on the behaviour of the settlements is presented.

**Table 4** - Physical parameters of construction materials used.

| Material | Property | Adopted value |
|---|---|---|
| Reinforced concrete | Specific weight (kN/m$^3$) | 25 |
| | Poisson coefficient | 0.2 |
| | fck(MPa) | 30 |
| | Elasticity modulus (GPa) | 30.67 |
| Pre-stressed cable | Diameter (mm) | 15.2 |
| | fptk(MPa) | 1900 |
| | fpyk(MPa) | 1710 |
| Ceramic masonry | Specific weight (kN/m$^3$) | 18 |
| Blocks of cement | Specific weight (kN/m$^3$) | 22 |

### 5.1. Variation of loads in columns

With the aim of quantifying the load variation on columns, considering the settlements or not, two hypotheses for the supports were considered in the analysis. In the first hypothesis the supports were considered as fixed, to obtain the reactions on the supports as is done traditionally in structural building projects. In the second hypothesis, the settlements measured at each stage were imposed, as prescribed displacements on the supports, to obtain the effects of the settlements on the reactions of the supports. By superimposing the effects of the weight of the structure itself and brickwork, prestressing and the settlements, the effects of the static SSI in the loads on columns were then analysed.

In order to quantify the influence of settlements on the loads, a redistribution coefficient of loads factor (*FR*) was employed. This factor is defined as:

$$FR = \left( \frac{R_\delta - R}{R} \right) \times 100 \tag{1}$$

where $R$ is the total reaction on column $i$ without considering its vertical displacements and $R_\delta$ is the total reaction on column $i$ taking into account its settlements. In these equations $R$ and $R_\delta$ are the total reactions obtained until the stage of construction being considered. Actually, the coefficient *FR* represents, in percentage terms, the increase or relief of the load on the support due to the settlements.

By taking the values of *FR* obtained it was possible to define two groups of columns with distinct behaviour. In the first group we have columns which suffered an increase in load when taking into account the settlement, and have positive *FR* values. In the second group we have those which suffered a decrease in load with negative *FR* values. Considering the maximum and minimum values of each group over the time of construction, it was possible to draw the curves show in Fig. 9. In this figure we also indicate, for each group, the columns which presented extreme values.

We find the highest load increases and reliefs in the first stages of construction. It can be seen that as the number of floors of the building increases, the amplitude between the values of load increases and relief among the columns tends to reduce. Symmetry of the curves is observed in relation to the horizontal axis that passes through the origin, indicating the redistribution of the forces that occurs, caused by the structure-soil interaction.

In the first half of the construction higher variations of loads are observed in deep foundations (columns P7, P8, P9 e P11) while in the second half higher values are observed in footing foundations (columns P23, P24, P25 e P30). This observation shows that, due to the stiffness of the structure, a transfer of loads still continues, even for foundations which end on the 2nd and 3rd floors.

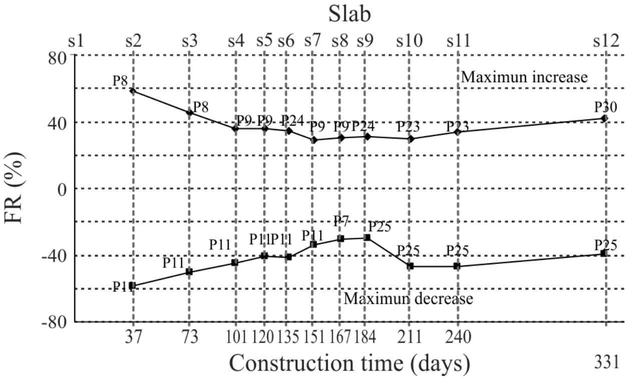


**Figure 9** - Variation in maximum load increase and relief during the course of construction.

A worrying fact can be observed in this figure. For almost all monitoring stages the value of *FR* for pillars suffering an additional load is more than 30%. For the last stage (the pouring of the 12th slab) this difference is about 43%. Note that at this stage a uniformization of settlements is attained and this difference may persist for the life cycle of the building. This increase is a cause for concern from a structural point of view, and therefore deserves attention.

Uniformity of load distribution may be found when we analyse the coefficient of variation (CV) of the redistribution factor (*FR*) for each stage of construction, as presented in Fig. 10. This coefficient of variation is defined by the ratio between the standard deviation and the mean of the *FR*s. It can be seen that with the increase in the number of floors, the redistribution factor tends to decrease and stabilize. This fact, as observed previously, is a consequence of making the settlements uniform due to the influence of the stiffness of the structure.

### 5.2. Evaluation of spring foundation coefficient

To perform the analysis of structures considering the foundation settlements, one of the simplifications adopted in the computational modelling assumes the use of an ideal spring, with a vertical degree of freedom, connected with the support points of the structure on the soil. This resource

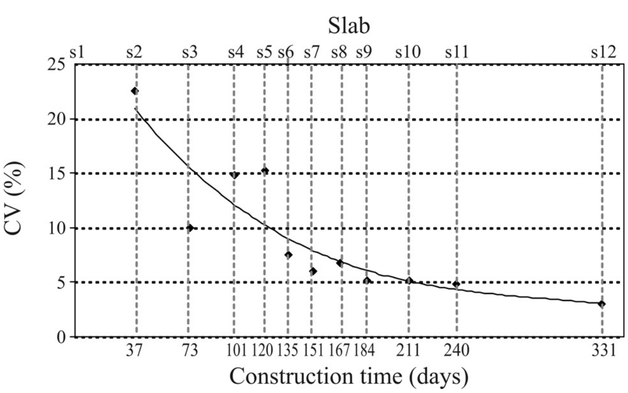


**Figure 10** - Variation coefficient of the load redistribution during the course of construction.

is incorporated in the computational design of structures as an option dealing with a more realistic representation of the behaviour of the structures.

In order to evaluate the magnitude of this parameter and to verify the feasibility of this assumption, we back-calculate here the spring coefficient based on experimental data. This spring coefficient of the soil-foundation set ($K_{sf}$) represents the relationship between the foundation load and the measured settlement and can be determined through Eq. (2),

$$R_{sf\,(i)} = \frac{R_{\delta(i)}}{\delta(i)} \quad (2)$$

where $K_{sf(i)}$ is the spring coefficient of the support *i*, $R_\delta$ is the reaction of the support *i* of the structure, until the stage of construction considered, when it is analysed considering the measured settlements $\delta_{(i)}$ of the same support.

Figure 11 shows the contours of the coefficient referring to the execution of the 12th slab. It is evident that the coefficient $K_{sf}$ is not constant along the ground surface, as also observed by Russo Neto *et al.* (2002) in their research carried out in a pre-cast concrete building. This can be explained by the fact that this coefficient is determined using the reactions of the supports when the measured settlements are considered. In this way, the values of $K_{sf}$ depend not only on the type of soil and foundation but also on the features of the structure of the building. Therefore, the hypothesis using the same spring coefficient for all foundations often used in design is not a feasible representation of the actual problem.

In Fig. 11 it is possible to see the formation of four distinct zones clustered according to the magnitude of *Ksf.* The peripheral region, defined as Zone A, has the lowest values of $K_{sf}$. Low values of $K_{sf}$ are also found in the zone near the lift shaft and stairs, defined as Zone B. The highest values of $K_{sf}$ are found in Zone D, in the neighbourhood of the columns P2 and P19. There is also an intermediate region, Zone C, located in the peripheral projection of the typical floor.

The average values of $K_{sf}$ during construction for the four zones described above are illustrated in Fig. 12. For zones C and D, we observe an increase of $K_{sf}$ values at the beginning of construction, when the soil is receiving a significant amount of load. At the end of construction, these zones present an increase of, approximately, 56% and 33%, respectively, compared with the initial values. On the other hand, zones A and B experience a decrease of this parameter of about 13% and 22%, respectively. In fact, both forces and settlements tend to increase over the time of construction. As regards the definition of $K_{sf}$, which is the ratio of these two quantities, regions A and B experience an increase in settlement higher than the increase in load, while different behaviour is observed in regions C and D. Thus, the redistribution of load as a function of settlement is also observed in this analysis.

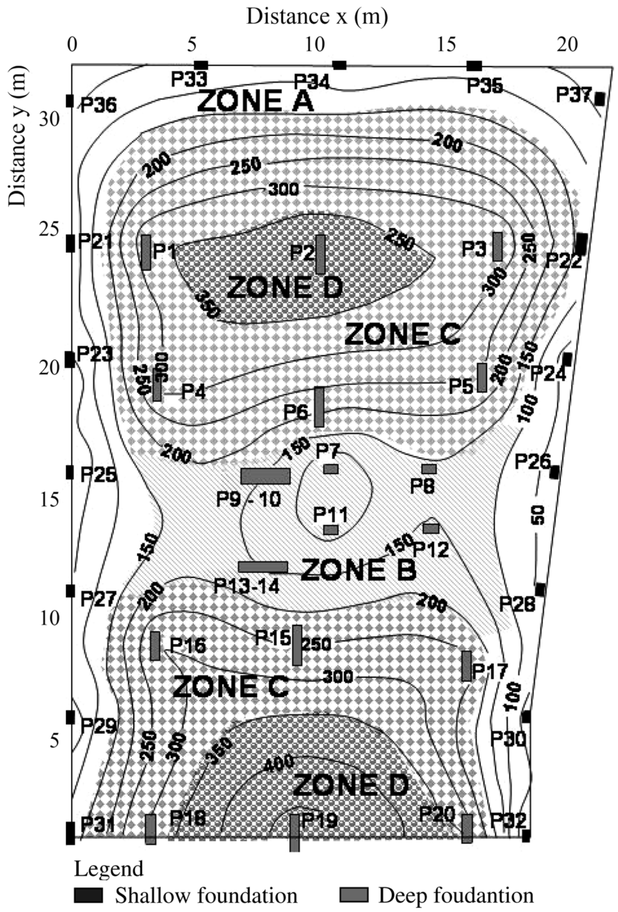


**Figure 11** - Contours of $K_{sf}$ for the last stage of construction (MN/m).

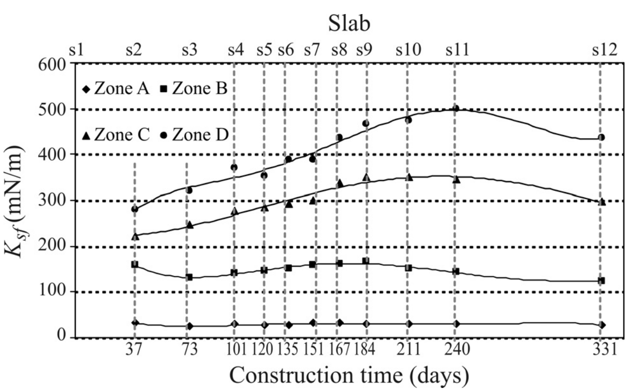


**Figure 12** - Curves of average values of $K_{sf}$ coefficient for zones SFA, SFB, SFC and SFD during construction.

It is clear that we have, again, a great disparity in the magnitude of this parameter among these four zones and during the construction of the building.

### 5.3. Influence of the stiffness of the structure on the static SSI mechanism

In this case study, the features of the structure make it difficult to use the methodology proposed by Meyerhof (1953), who considered, for the static SSI analysis, the frame of the structure as an equivalent beam. Thus, in order to analyse the influence of the stiffness of the structure on the redistribution of loads, another procedure was adopted. In this procedure, a parameter, defined here as an equivalent stiffness of the structure on each support ($K_e$), was obtained by applying unit settlements for each support and for each stage of construction. The necessary forces, that is, reaction values, to keep this displacement were interpreted as a stiffness coefficient of the structure related to a unit settlement of each support. It is important to stress that this procedure is similar to the idea of the direct displacement method for determination of the stiffness matrix of any kind of structure.

The variation of this parameter along the ground surface, for the 12th stage, can be observed in Fig. 13, where contours of $K_e$ values are plotted. With regard to this figure, three distinct zones can be recognized according to the magnitude of the values of $K_e$. First, the zone called RA is characterized by lower values of $K$, of about 40 MN/m. This region corresponds to the periphery of the ground where the columns end in the second slab. Along the radial direction from the centre of the building, it is possible to observe a second region, called RB, with values of $K_e$ between

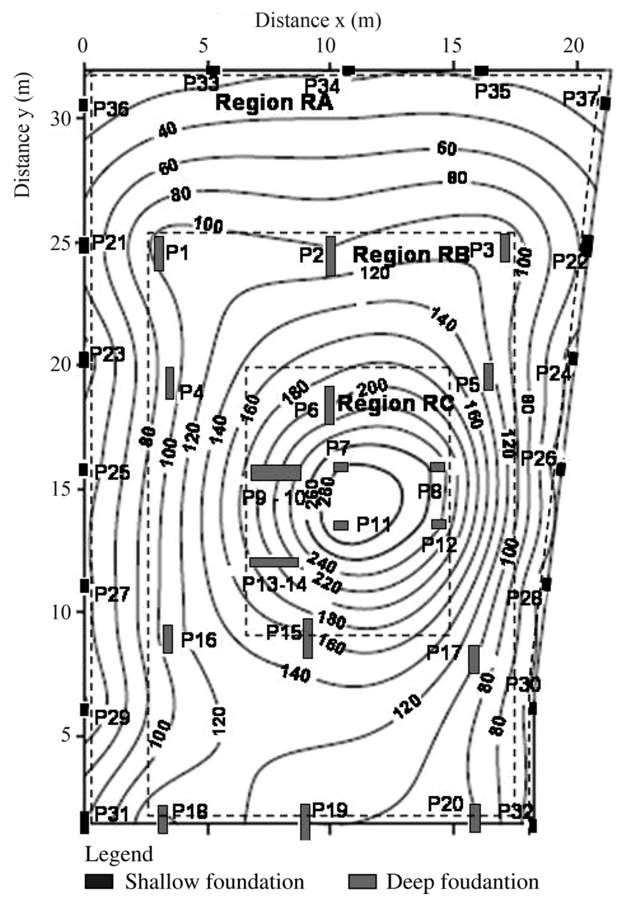


**Figure 13** - Contours of equivalent coefficient curves ($K_e$) for the last stage of construction (MN/m).

80 MN/m and 120 MN/m. Finally, the third zone, located in the centre, called RC, has values of $K_e$ over 160 MN/m.

In order to visualize the evolution of this parameter during the time of construction, the curves of mean values of $K_e$ for regions RA, RB and RC are plotted in Fig. 14. It can be observed that regions RB and RC show a significant increase in the values of $K_e$ during construction, but tend to stabilize in the final stages. On the other hand, the mean values in region RA stabilize just after the execution of the third slab. It should be noted that the columns in this region have shallow foundations and end at this stage of construction.

Another interesting result can be obtained if we compare Fig. 10 with Fig. 15 plotted below. The latter shows the variation curves of $K_e$ during the construction stage, proportionally to the maximum values calculated for each region. It can be seen that all regions reached almost half the value of total stiffness after the third slab execution. Analysing Fig. 10, we can see that, after the execution of the fourth slab, the variation of the redistribution of load decreases. In other words, this confirms that significant effects of static SSI take place in the initial stages of construction. The same was observed by other researchers, like Gusmão & Calado Jr. (2002), Gonçalves (2004), Barros (2005), Danziger (2000) and Gusmão (2006).

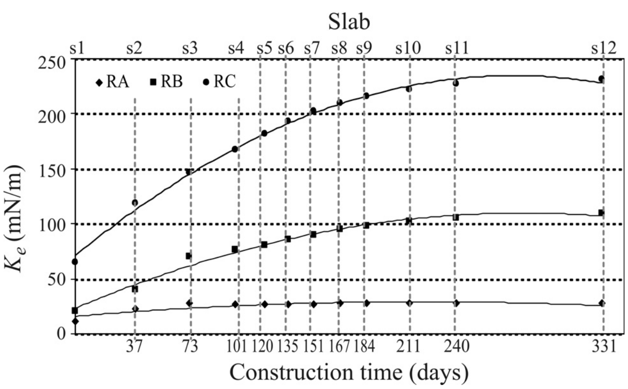


**Figure 14** - Variation of the equivalent stiffness coefficient ($K_e$) for regions RA, RB and RC during construction.

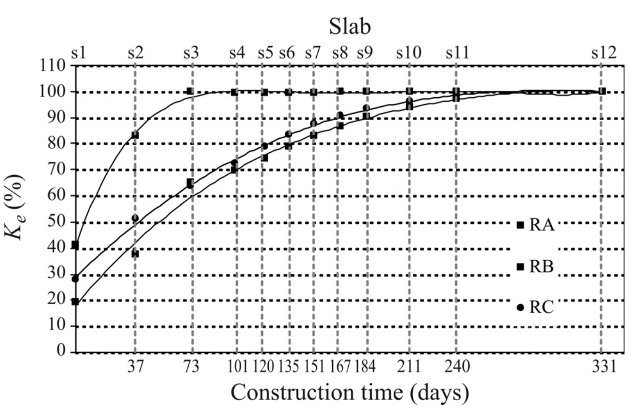


**Figure 15** - Proportional evolution of the equivalent stiffness coefficient ($K_e$) of the structure for regions RA, RB and RC.

An analysis of the evolution of measured settlements was performed for each stage of construction and the results are plotted in Fig. 16. The initial stage of construction was characterized by a large displacement, generated by the removal of the casting forms of the first slab and execution of the second. It is possible to verify a uniform increase of settlements over time, which could be justified by the constant velocity imposed on the construction.

Figure 16 can also provide significant information on the static SSI mechanism. As observed, the average settlements in shallow foundations (region RA) have the same magnitude as in deep foundations in the first stages of construction. After the execution of the third slab, they continue to grow slightly and stabilize in the last stages. The increase of settlements in shallow foundations after the third pour slab suggests that, due to the stiffness of the structure, a transfer of loads from the central columns to the edge columns occurred. This effect is typical of the static SSI mechanism, as described in section 2.

Also in Fig. 16 the average loads for each stage of construction and for each section is provided. Note that there is a correlation between regions RA, RB and RC of Fig. 13 and zones A, B, C and D of Fig. 11. In fact, zone A corresponds to region RA, zone B corresponds to region RC and zones C and D correspond to region RB. In this way, we can observe the evolution of the stiffness coefficient in these regions by taking into account the evolution of the stiffness coefficient $K_{sf}$ of Fig. 12.

In Fig. 17 an iso-settlement curve is presented for the stage related to the execution of the last slab. It is possible to observe the formation of a settlement basin, with higher depressions in the central region of the ground. This depression is due to the typical floors which generate the loads responsible for the increase of settlements in this region.

The influence of the stiffness of the structure on settlements can be verified using the variation coefficient of settlements, which is plotted in Fig. 18, and using the information provided by Fig. 13. Figure 16 shows, especially with regard to region RC, that the variation in settlement

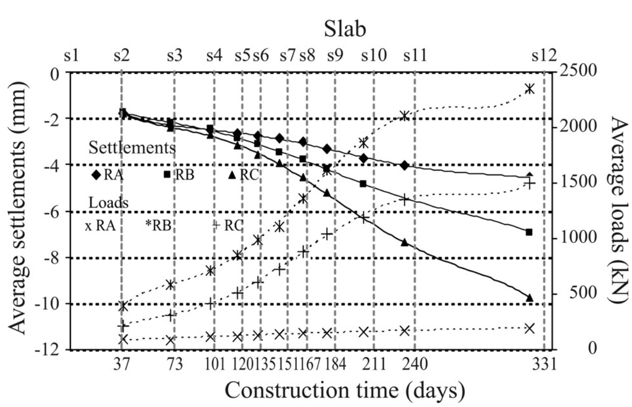


**Figure 16** - Evaluation of mean settlement and loads during construction.

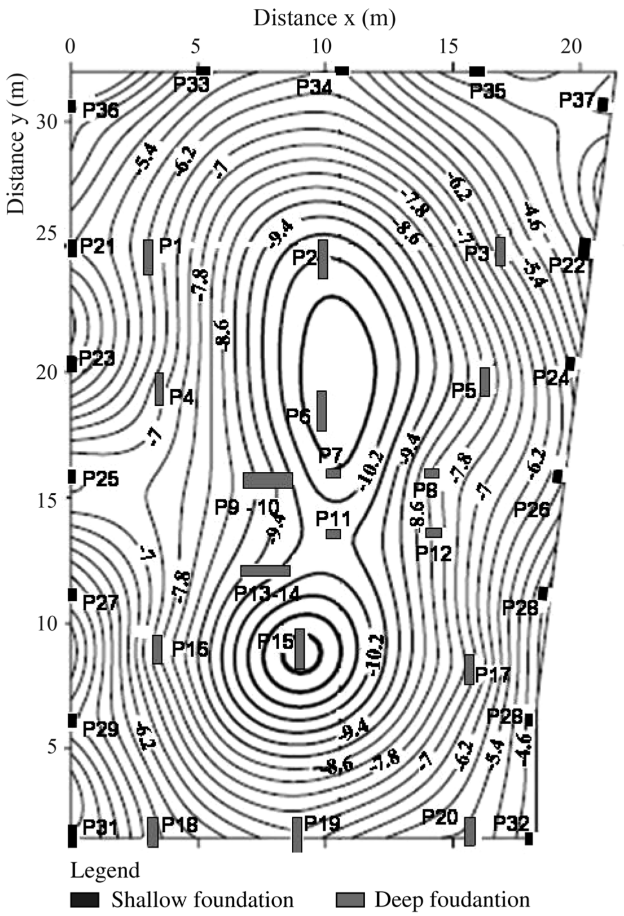


**Figure 17** - Iso-settlement curve for stage 12.

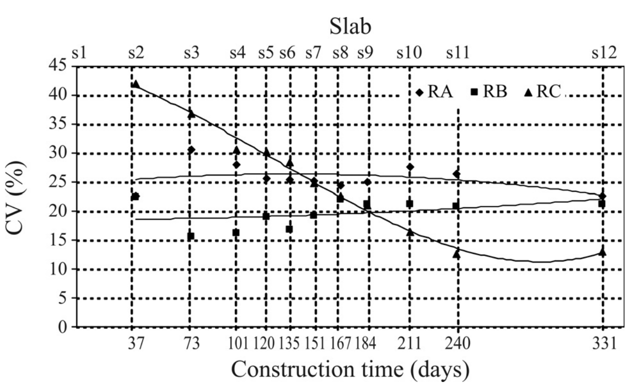


**Figure 18** - Evolution of the settlement variation coefficients for regions RA, RB and RC over time of construction.

coefficient decreases over the time of construction, while the structure experiences an increase of the parameter $K_e$. This effect is more significant for the later stages of construction, where we have higher values of $K_e$. Thus, we suppose that the stiffness of the structure promotes the uniformization of settlements, as observed by Gusmão (1994), Danziger *et al.* (2000) and Gusmão (2006) in their respective research. Thus, the restriction of the structure to settlements depends on the number of floors and this dependence is more significant in the early stages of construction.

## 6. Conclusions

This work aimed to investigate the static soil-structure interaction mechanism. To achieve this, the behaviour of a structure which had its settlement monitored from the beginning of construction was analysed. The importance of this mechanism was demonstrated by analysing the behaviour of certain parameters, such as the redistribution of loads among columns, the spring soil coefficient and the stiffness of the structure. In general, it was found that:

• Numerical simulation of the building considering the execution of each slab and the two hypotheses, one with non-displaceable supports and other with the settlements applied to each model, was useful for evaluating the effects of settlements.

• The small settlements that occur in buildings, and which are frequently disregarded, cause disturbances in the structure, resulting in redistribution of loads among columns, with consequent greater uniformity of settlements.

• The hypothesis, often adopted in projects, which considers the support of foundations by means of a constant spring coefficient does not represent the real situation of the structure. In fact, the use of a spring coefficient in foundations must take into account not only the rigidity of the soil but also the rigidity of the structure because, according to the results obtained, these coefficients vary among the foundation elements.

• Due to the static SSI, a transfer of loads occurs from the columns which tend to settle more to those that tend to settle less. Load transfer among the columns causes a trend towards uniformization of settlements, resulting in smaller displacements than those estimated.

When observing the effects of the soil-structure interaction, it was concluded that it is of extreme importance to consider the settlements in the analysis of the structure. It is also important to include this procedure in drawing up projects in order to analyse their effects on the construction process.

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