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INFLUENCE OF THE SHAPE OF REINFORCED CONCRETE BUILDINGS ON SOIL-STRUCTURE INTERACTION

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Abstract: The aim of this paper is to study the effect of the plan shape of reinforced concrete buildings on the soil-structure interaction mechanism. To this end, two finite element models are developed using the SAP2000 program: (i) a three-dimensional model with a square floor plan and (ii) a three-dimensional model with a rectangular floor plan. Indisplaceable supports and spring supports were used for the analysis. The results of the square plan model are similar to those of the rectangular plan model, i.e. when soil-structure interaction is taken into account, there is a redistribution of forces in the structural elements. The peripheral columns showed an increase in stress, while the central columns showed a reduction in stress. There was an increase in positive moments in the spans and negative moments in the peripheral supports of the central beam at ground level. In other words, if the structural design does not take into account settlements (in the case of a design without soil-structure interaction), the settlements, by producing a bending moment diagram that is different from the one predicted, can lead to localized plasticization in the beams. It is worth noting that for the rectangular floor plan, which has higher differential settlement values, the effect of soil-structure interaction is even more relevant in the design, not only of the foundations, but also of the structure.
Keywords: Building plan form, reinforced concrete, soil-structure interaction.

INTRODUCTION

The deformability of the foundations can influence the distribution of stresses in the superstructure. Therefore, the analysis of soil-foundation-superstructure interaction must be taken into account when calculating the displacements and internal forces of the superstructure/infrastructure assembly. The analysis that takes these factors into account at the design stage is called soil-structure interaction.

What can be observed in studies of soil-structure interaction is that, in general, there is a transfer of stresses from the supports that tend to settle more to those that settle less. It can be seen that the external pillars of buildings tend to experience an increase in stresses and the internal pillars a decrease in stresses. In addition, the soil-structure interaction also affects the stresses of girders and lower beams. The increase in stresses on these elements (disregarded in simplistic analyses) can represent a risk to the structure depending on the magnitude of the increase. Gusmão [1] mentions that theoretical and real-life analyses prove the importance of soil-structure interaction in building design, which can lead to more economical and safer projects.

Aoki [2] and [3] proposed a simple model of isolated vertical load transfer for the soil mass and, later, for the case of a group of piles and a group of blocks interconnected by the superstructure. For the calculation of structures considering soil-structure interaction, he suggested the following procedure: initially, the structural engineer calculates the loads on the columns, considering that the foundations are indisplaceable. Based on these loads, the foundation engineer estimates the settlements, considering that the stiffness of the structure is zero, obtaining the settlement basin. The structural engineer divides the stresses by the settlements and obtains the initial spring coefficients in each column, and recalculates the stresses in the columns, considering the structure on elastic supports. Based on these new stresses, the foundation engineer recalculates the settlements, considering that the stiffness of the structure is zero, obtaining a new settlement basin. The structural engineer re-evaluates the new spring coefficients based on this new settlement basin, recalculates the stresses and sends them to the geotechnical engineer. The process is iterative until the desired convergence is reached. The above procedure is only valid for linear elastic soil behavior, which is a valid approximation only for sandy soils. In the case of clay soils, the same procedure is valid, but the estimation of the settlement involves a soil model that includes not only the settlement value, but also its velocity, which is related to the densification coefficient of the soil.

Some influential factors in soil-structure interaction are the relative stiffness of the structure-soil, the construction sequence, the number of floors in the building, the presence of girders, the three-dimensional frame effect and the plan form of the building.

This article studies the effect of the building's plan form. To this end, two finite element models are developed using the commercial structural analysis program SAP2000 (version 15) [4]. The floor plan of the first three-dimensional model is square and that of the second is rectangular. Indisplaceable supports and spring supports are used for the analysis (the soil profile is low-compact sand for both models). The stiffness coefficients of the spring supports are defined using the proposal by Poulos and Davis [5].

CHARACTERISTICS OF BUILDINGS AND THEIR FOUNDATIONS

The buildings under study are made of reinforced concrete and have four floors. The ceiling height is a single three meters. The buildings have double symmetry and the floor plan of the first model (square plan) is shown in Figure 1.

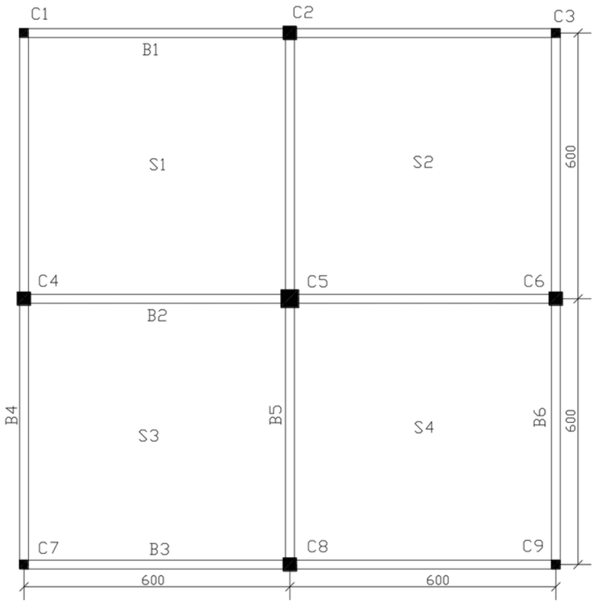


Figure 1. Square floor plan of the building (measurements in centimeters).

Figure 1 shows that the building has 9 pillars reaching up to the foundations. Pillars C1, C3, C7 and C9 have a cross-section of 20 x 20 centimeters. Pillars C2, C4, C6 and C8 have a cross-section of 30 x 30 centimeters and pillar C5 has 40 x 40 centimeters. All the beams have a cross-section of 20 x 80 centimeters. The slabs are 10 centimeters high.

Figure 2 shows the floor plan of the second model (rectangular floor plan).

Figure 2 shows that the building has 12 pillars reaching up to the foundations. Pillars C1, C4, C9 and C12 have a cross-section of 20 x 20 centimeters. Pillars C2, C3, C5, C8, C10 and C11 have a cross-section of 30 x 30 centimeters and pillars C6 and C7 have 40 x 40 centimeters. All the beams have a cross-section of 20 x 80 centimeters. The slabs are 10 centimeters high.

For the two models, square and rectangular, the stresses are due to the weight of the building itself and an overload on the slabs of 3 kN/m^2. The material properties of the superstructure (slabs, beams and columns) are f_{ck} concrete 21 MPa, specific weight 25 kN/m^3, modulus of elasticity E=25700 MPa and Poisson's ratio 0.2. The foundations are pre-

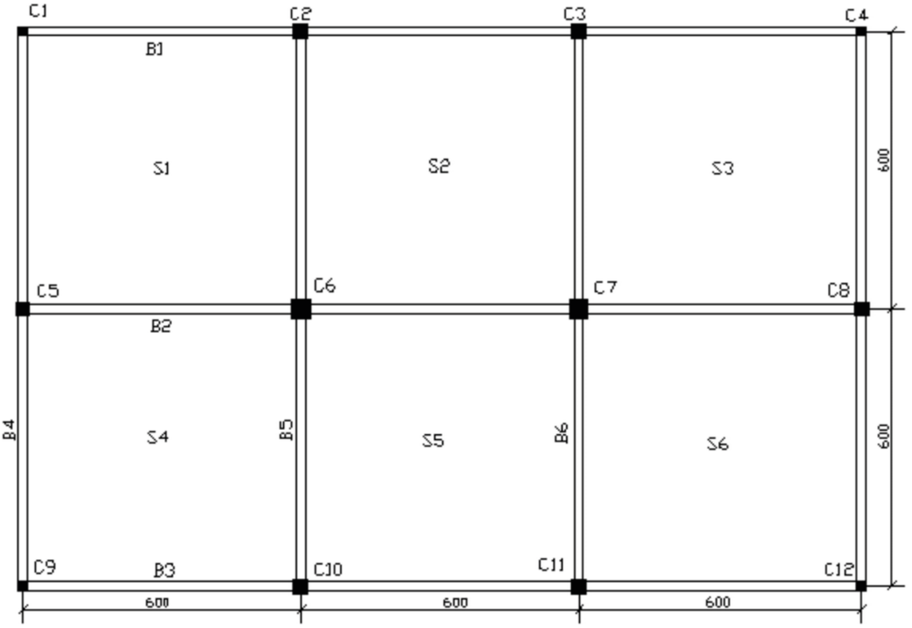


Figure 2 - Rectangular floor plan of the building (measurements in centimeters).

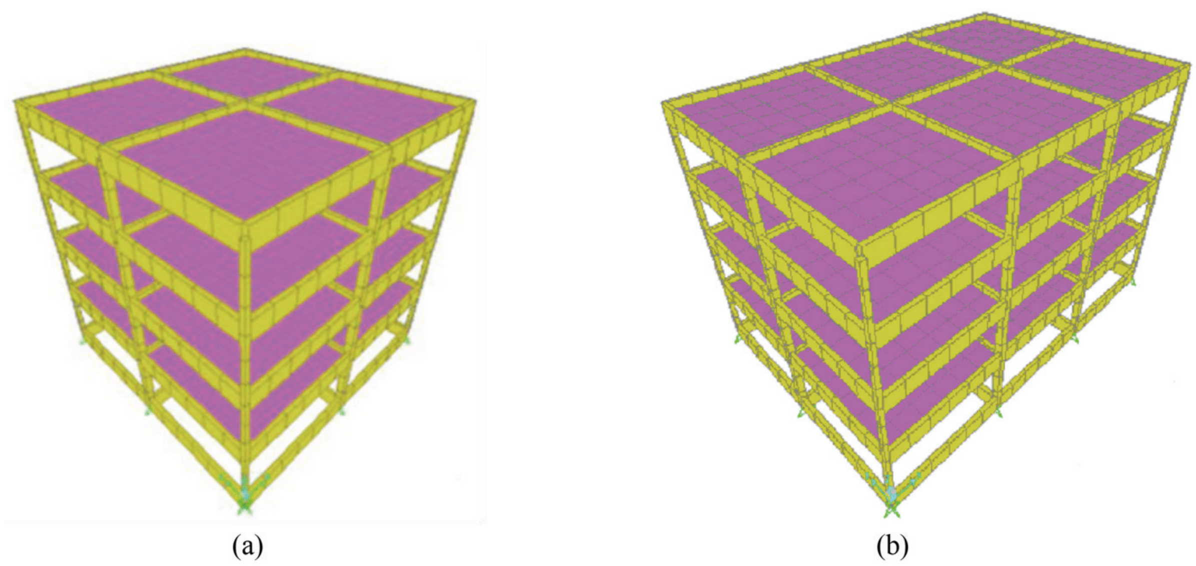


Figure 2. (a) Three-dimensional model of the building with a square plan and (b) Model with a rectangular plan.

cast concrete piles (insulated) with diameters of 30, 40 and 60 centimeters, driven 14 meters into a thick layer of low-compact sand ($E = 9$ MPa and $v = 0.2$).

COMPUTER MODELING OF REINFORCED CONCRETE BUILDINGS

The structures were discretized into finite elements using the commercial structural analysis program SAP2000 (Version 15) [4]. Bar elements were used for the beams and columns and shell elements for the slabs and masonry.

Figure 2(a) shows the three-dimensional model with a square floor plan and Figure 2(b) the model with a rectangular floor plan.

Indisplaceable supports and spring supports are used for the analysis. The stiffness coefficients of the supports (K) are defined from Equation 1:

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

Where:

Q is the load (kN).

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

POULOS AND DAVIS MODEL FOR PILE SETTLEMENT ESTIMATION

Poulos and Davis [5] presented a rational method for estimating pile settlements, based on a numerical procedure using Mindlin's equations [6]. The method, presented in the form of abacuses, makes it possible to predict the settlement of an isolated pile, initially assumed to be incompressible, in a semi-infinite and homogeneous elastic medium. Subsequently, corrective factors were developed to take into account the influence of the pile's compressibility, the position of a boundary considered rigid (or indisplaceable), the Poisson's ratio and the improvement of the soil at the base level.

For a pile of diameter or width B, embedded in a mass with Young's modulus E, loaded (in compression) by at its top, the top settlement is given by Equation 2:

$$w_0 = \frac{Q_0 I}{EB} \quad (2)$$

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

$$I = I_0 R_k R_h R_v R_b \quad (3)$$

Where:

I_0 is the influence factor for an incompressible pile in a homogeneous medium.

R_k is the factor that takes into account the compressibility of the pile.

R_h is the factor that takes into account the presence of a rigid wall below the pile tip.

R_b is the factor that considers a stiffer soil below the pile base.

RESULTS AND DISCUSSIONS

Table 1 shows the values of normal forces obtained in the columns, without considering soil-structure interaction and with interaction, for the structural model with a square plan. Table 2 shows the normal forces obtained in the columns, without considering soil-structure interaction and with interaction, for the structural model with a rectangular floor plan.

From Table 1 (square plan model), it can be seen that in the second analysis, with displaceable supports (with values of k), new loads and settlements were produced (as the analysis is linear, the variations in loads and settlements are naturally the same). The peripheral pillars had their loads increased (the difference was 44%) and the internal pillars had their loads decreased (a difference of 25%), i.e., as reported by Gusmão [1], there was a redistribution of forces in the pillars. Similar behavior is observed in Table 2, which shows the results for a rectangular floor plan model. There was an increase in load of around 37% on the peripheral pillars and a relief of 19% on the central pillars.

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).

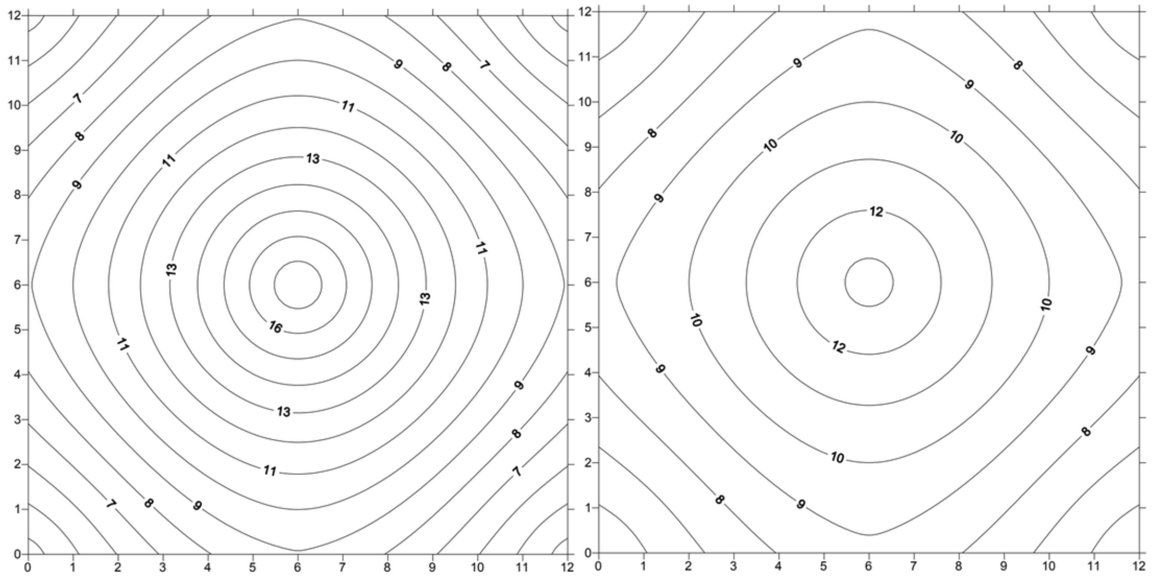
Table 1. Normal forces obtained in the columns, without considering soil-structure interaction and with interaction, for the square plan model.

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).

Table 2. Normal forces obtained in the columns, without considering soil-structure interaction and with interaction, for the rectangular plan model.



(a) (b)

Figure 3: Settlement basin for the square-plank model (a) without soil-structure interaction and (b) with interaction.

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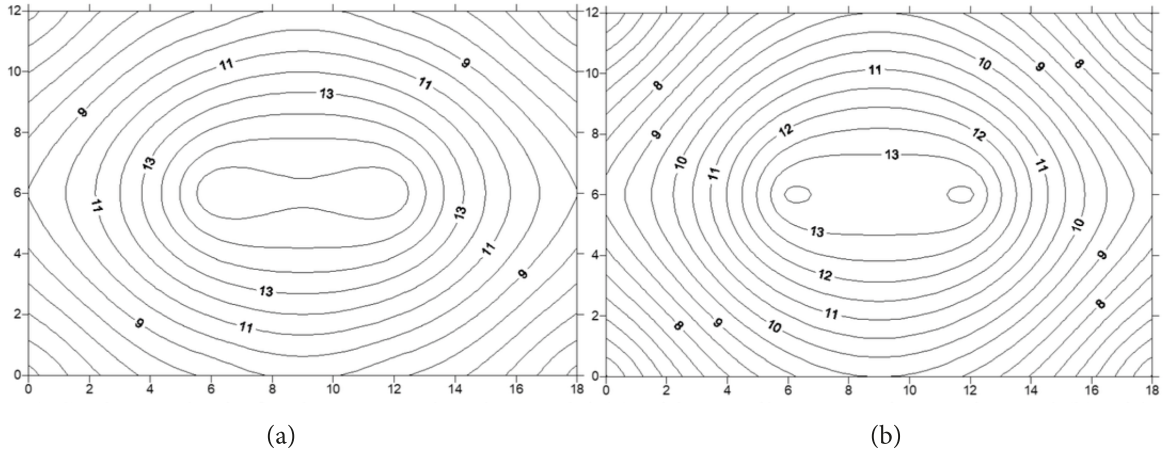

Figure 4: Settlement basin for the rectangular plan model (a) without soil-structure interaction and (b) with interaction.

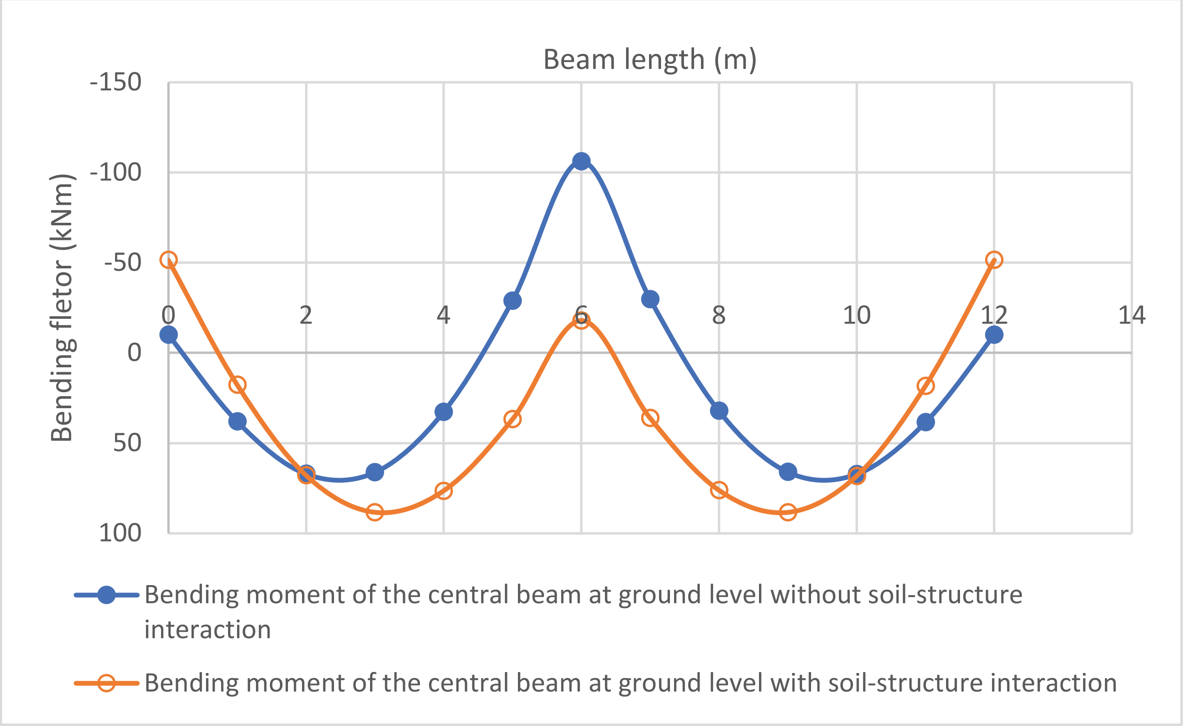

Figure 5 - Bending moment diagram of the central beam at ground level, without considering soil-structure interaction and with interaction for the square plan model.

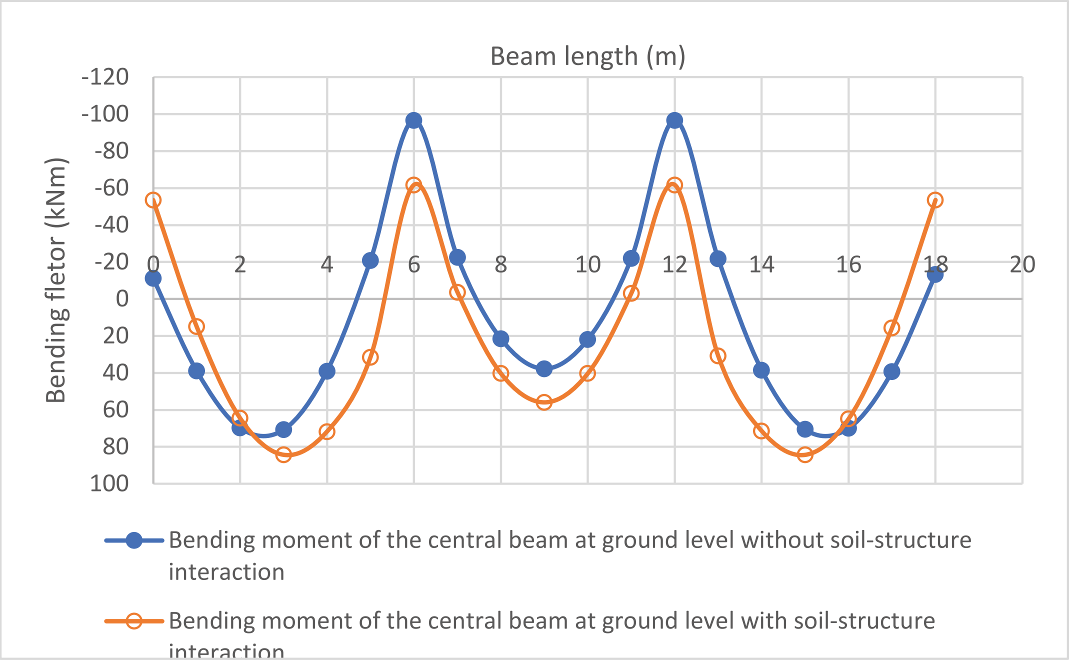

Figure 6. Bending moment diagram of the central beam at ground level, without considering soil-structure interaction and with interaction for the rectangular plan model.

Figure 3 shows the settlement basin without considering soil-structure interaction and considering it for the square plan model. Figure 4 shows the settlement basin without considering soil-structure interaction and taking it into account for the model with a rectangular floor plan.

Figures 3 and 4 show the effect of soil-structure interaction on the tendency to uniform settlement. It can also be seen that the plan with a square geometry shows a greater tendency to uniform settlement than the plan with a rectangular geometry. In fact, Barata [7] emphasized that the closer the building plan is to a square, the greater the tendency to uniform settlement.

Figures 5 and 6 illustrate, respectively, the bending moment diagrams of the lower central beam (first floor) for the square plan model and the rectangular plan model for the two situations analyzed, i.e. without soil-structure interaction and with interaction. The lower central beam was selected because the lower girders and beams are the ones that suffer the most from settlement.

Figure 5 shows an increase in the positive moments in the spans (a difference of around 25%) and also a considerable increase in the negative moments in the peripheral supports (a difference of around 80%). Figure 6 shows an increase in the positive moments in the spans (a difference of around 33% in the central span) and also an increase in the negative moments in the peripheral supports (a difference of around 80%). It can be seen that, for both square and rectangular floor plan geometries, there is a change in the stress values due to settlement. What happens in practice is that, if the structural design does not take settlements into account (in the case of design without soil-structure interaction), settlements, by producing a different bending moment diagram to that predicted, can lead to localized plasticization in the beams.

It can be seen that in cases where the settlements are significant, the effect of soil-structure interaction is important in the design, not only of the foundations, but also of the structure. There are reports of buildings in Santos that have suffered large settlements and have seen the crushing of peripheral pillars, as well as intense cracking of the first levels of beams.

CONCLUSIONS

The conclusions are as follows:

(i) The results of the square plan model are similar to those of the rectangular plan model, i.e. when soil-structure interaction is taken into account, there is a redistribution of forces in the structural elements

(ii) The peripheral columns showed an increase in stress, while the central columns showed a reduction in stress.

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

(iv) There was a greater tendency for differential settlements to be uniform in the model with a square plan, i.e. the closer the plan of the building is to a square, the greater the tendency for settlements to be uniform.

(v) There was an increase in positive moments in the spans and negative moments in the peripheral supports of the central beam at ground level. This means that if the structural design does not take into account settlements (in the case of a design without soil-structure interaction), the settlements, by producing a bending moment diagram that is different from the one predicted, can lead to localized plasticization in the beams.

(vi) From this study, we can see the importance of computer models for understanding the mechanism of soil-structure interaction and, furthermore, in cases where settlements are significant, the effect of soil-structure interaction is relevant in the design, not only of the foundations, but also of the structure.

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