v. 4, n. 11, 2024

Journal of
Engineering
Research

ELASTIC ANALYSIS OF THE INFLUENCE OF MASONRY ON THE SOIL-STRUCTURE INTERACTION OF A REINFORCED CONCRETE BUILDING

Mariana Larissa Antunes da Costa
Graduation student in Civil Engineering, ``Universidade Federal de Juiz de Fora, Juiz de Fora``, Brasil

Juliane Crisitna Gonçalves
Professor, ``Universidade Federal de Juiz de Fora``, Juiz de Fora, Brazil

DOI https://doi.org/10.22533/at.ed.3174112412049

Abstract: The present work aims to study the influence of masonry on the soil-structure interaction mechanism for a reinforced concrete building. To this end, two finite element models are developed using the SAP2000 program, namely: (i) three-dimensional model without masonry and (ii) three-dimensional model with discretized masonry. This last model, closer to reality, provides greater rigidity to the superstructure. Non-displaceable supports and spring supports are used for the analyses. The results of the model with discretized masonry are similar to those of the model without masonry, that is, when considering the soil-structure interaction, a redistribution of efforts in the structural elements was observed. The peripheral pillars showed an increase in load while the central pillar showed a relief in load. A tendency towards uniformity of differential settlements was observed, especially in the model with discretized masonry and, also, an increase in positive moments in the spans and in negative moments in the peripheral supports of the central beam at the ground floor level. In other words, if the structural design does not consider settlements (case of design without soil-structure interaction), the settlements, by producing a bending moment diagram different from that predicted, can lead to localized plasticization in the beams. Thus, the importance of refined models can be seen and, in cases where settlements are significant, the effect of soil-structure interaction is relevant in the project, not only of the foundations, but also of the structure.

Keywords: Masonry, Soil-Structure Interaction, Reinforced Concrete.

INTRODUCTION

The consideration of soil-structure interaction is increasingly being incorporated into structural design practice by structural and foundation design companies. Recently, the latest version of ABNT NBR 6122 [1], in its item 5.5, establishes that “in structures in which the deformability of the foundations can influence the distribution of efforts, the soil-structure interaction must be studied”. This recommendation from the Brazilian standard further reinforces the importance of taking soil-structure interaction into account in project design.

There are several works that contribute to the topic of soil-structure interaction, highlighting the pioneering work of Meyerhof [2], Chamecki [3] and Goschy [4]. More recent works are found, but the vast majority address dynamic effects, arising from earthquakes, not implying a more practical and everyday nature for structural and geotechnical designers.

Aoki [5] and [6] proposed a simple model of isolated vertical load transfer for the soil mass and, subsequently, for the case of a group of piles and a group of blocks interconnected by the superstructure. To calculate the structures considering the soil-structure interaction, he suggested the following procedure: initially, the structural engineer calculates the loads on the pillars, considering that the foundations are indisplaceable. Based on these requests, the foundation engineer estimates the settlements, considering that the structure’s stiffness 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 requests, the foundation engineer recalculates the settlements, considering that the structure’s stiffness is zero, obtaining a new settlement basin. The structural engineer reevaluates the new spring coefficients, based on this new settlement basin, recalculates the requests and sends them to the geotechnical engineer. The process is iterative, until the desired convergence is achieved. The previous procedure is only valid for linear elastic behavior of the soil, which is an approximation valid only for sandy soils. In the case of clayey soils, the same procedure is valid, but the settlement estimate involves a soil model that takes into consideration, not only the settlement value, but also its speed, which is related to the soil consolidation coefficient.

Gusmão [7] mentions that one of the effects caused by soil-structure interaction is a redistribution of efforts in the structural elements, especially the loads on the pillars. He also mentions that theoretical analyzes and real case studies prove the importance of soil-structure interaction in building projects, which can lead to more economical and safe projects.

It is in this context that this article is inserted. The influence of masonry on the soil-structure interaction mechanism for a reinforced concrete building is studied. To this end, two finite element models were developed using the commercial structural analysis program SAP2000 (version 15) [8], namely: (i) three-dimensional model without masonry and (ii) three-dimensional model with discretized masonry. Non-displaceable supports and spring supports are used for the analyses. The stiffness coefficients of spring supports are defined based on the relationship between the normal effort in the support and the settlement estimated using the proposal by Poulos and Davis [9].

CHARACTERISTICS OF THE BUILDING AND ITS FOUNDATIONS

The building under study is made of reinforced concrete and has four floors. The ceiling height is unique, measuring three meters. The building has double symmetry and the plan is shown in Figure 1.

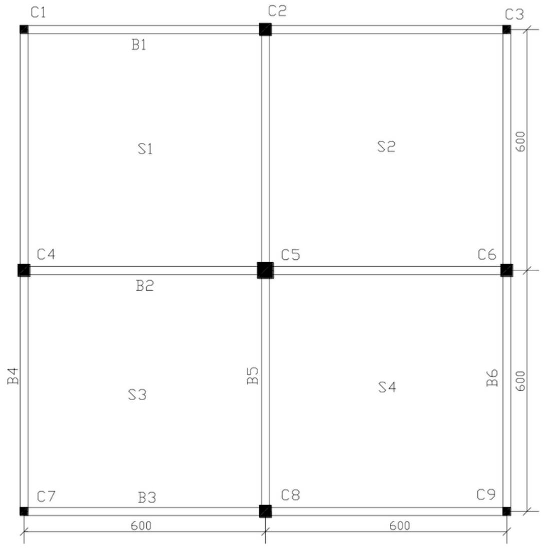


Figure 1. Floor plan of the building (measurements in centimeters).

From Figure 1, it can be seen that the building has 9 pillars reaching 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 is 40 x 40 centimeters. All beams have a cross section of 20 x 80 centimeters. The slabs are 10 centimeters high.

The requests arise from the self-weight of the work and an overload on the slabs of 3 kN/m². The material properties of the superstructure (slabs, beams and pillars) are f_{ck} concrete 25 MPa, specific weight 25 kN/m³, modulus of elasticity $E = 248000$ MPa and Poisson's ratio 0.2.

The masonry is assumed to be 15 centimeters thick and with a specific weight of 16 kN/m³.

The foundations are pre-cast concrete piles (isolated) with diameters of 30, 40 and 60 centimeters, driven 14 meters into a thick layer of low compactness sand ($E = 9$ MPa and $\nu = 0.2$).

MODELING REINFORCED CONCRETE BUILDING COMPUTING

The structure was discretized into finite elements using the commercial structural analysis program SAP2000 (Version 15) [8]. Bar elements were used for beams and pillars and shell elements were used for slabs and masonry.

Figure 2(a) shows the three-dimensional model without masonry and Figure 2(b) the model with masonry.

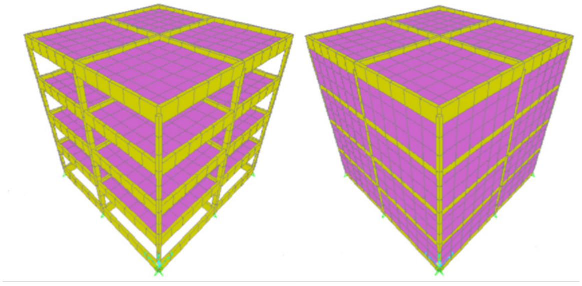

(a) (b)

Figure 2. (a) Three-dimensional model of the building without masonry and (b) Model with masonry.

Non-displaceable supports and spring supports are used for the analyses. The support stiffness coefficients (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 settlement estimated for the piles from Poulos and Davis [9]

POULOS AND DAVIS MODEL FOR PILE SETTLEMENT ESTIMATION

Poulos and Davis [9] presented a rational method for estimating pile settlements, based on a numerical procedure, which employs Mindlin's equations [10]. The method, presented in the form of abacus, allows predicting 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 consider 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 foundation with Young's modulus E, loaded (in compression) at Q_0 its top, the settlement at the top is given by Equation 2:

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

Equation 3 provides the more general influencing 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 incompressible pile in homogeneous medium.

R_k is the factor that considers the compressibility of the pile.

R_h is the factor that considers the presence of a rigid boundary below the tip of the pile.

R_b is the factor that considers a more rigid soil below the base of the pile.

RESULTS AND DISCUSSIONS

Table 1 presents the normal effort values obtained in the columns, without considering the soil-structure interaction and with the interaction, for the structural model without masonry. Table 2 presents the values of normal efforts obtained in the columns, without considering the soil-structure interaction and with the interaction, for the structural model with the masonry discretized into finite elements.

From Table 1, it can be seen that in the second analysis, with displaceable supports (with k values), 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 load reduced (difference of 25%), that is, as reported by Gusmão [7], there was a redistribution of efforts in the pillars. The same behavior is observed in Table 2, which presents a more refined model (closer to reality) with the discretization of the masonry. The introduction of masonry into the model represents an increase in the rigidity of the superstructure. An increase in load of around 36% was noted on the peripheral pillars and a relief of 24% on the central pillar.

Figure 3 shows the settlement basin without considering the soil-structure interaction and considering it for the model without masonry. Figure 4 illustrates the settlement basin without considering the soil-structure interaction and considering it for the model with discretized masonry.

From Figures 3 and 4, the effect of the soil-structure interaction of a tendency towards uniformity of settlements can be observed. The discretization of the masonry further contributed to a greater uniformity of the differential settlements.

Figure 5 illustrates the bending moment diagrams of the lower central beam (ground floor) for the model with discretized masonry (closer to reality) for the two situations analyzed, that is, without considering the soil-structure interaction and with the interaction. This beam was selected because the lower straps and beams are those that suffer most from settlements.

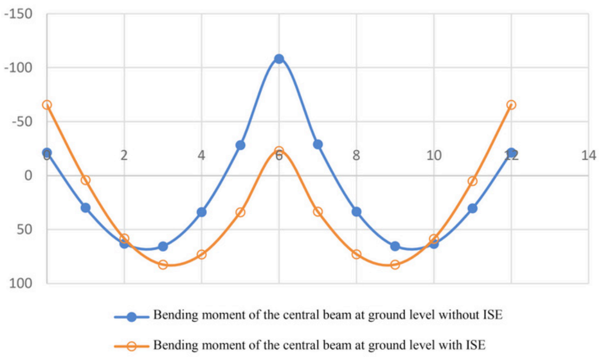


Figure 5. Diagram of bending moments of the central beam at ground level, without considering the soil-structure interaction and with the interaction.

From Figure 5, we can see an increase in positive moments in the spans (difference of around 20%) and also a considerable increase in negative moments in peripheral supports (difference of approximately 67%). What happens in practice is that, if the structural design does not consider settlements (in the case of a project without soil-structure interaction), the settlements, by producing a bending moment diagram different from that predicted, can lead to localized plasticization in the beams.

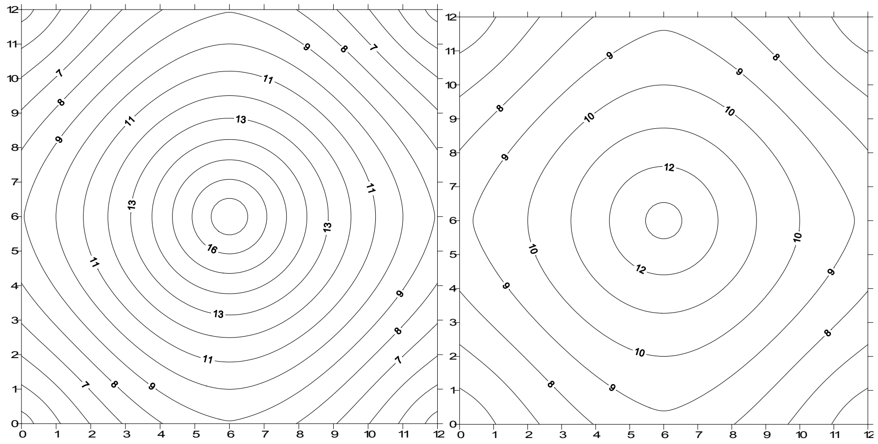
It can be seen that, in cases where settlements are significant, the effect of soil-structure interaction is important in the design, not only of the foundations, but also of the structure. There are reports of buildings in Santos that suffered major settlements and showed crushing of peripheral pillars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

Corner stone	Without interaction				With interaction		Difference (%)	
	Load KN	Repression PE*	Repression PG*	k = Q/w (kN/m)	Load (KN)	Repression NM	In the load	In the repression**
C1	207	0	3,5	59143	298	5,05	44	44
C2	593	0	8,9	66629	585	8,8	-1	-1
C5	1323	0	18,0	73500	994	13,5	-25	-25
*PE. = Structural design (without interaction); Pg = initial geotechnical design (without interaction)								
**Difference in relation to the forecast in the initial geotechnical project (without interaction)								

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

Corner stone	Without interaction				With interaction		Difference (%)	
	Load KN	Repression PE*	Repression PG*	k = Q/w (kN/m)	Load (KN)	Repression NM	In the load	In the repression**
C1	282	0	4,8	58750	384	6,51	36	36
C2	705	0	10,6	66509	685	10,3	-3	-3
C5	1414	0	19,2	73646	1076	14,6	-24	-24
*PE. = Structural design (without interaction); Pg = initial geotechnical design (without interaction)								
**Difference in relation to the forecast in the initial geotechnical project (without interaction)								

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



(a) (b)

Figure 3. Settlement basin for the model without masonry (a) without considering the soil-structure interaction and (b) with the interaction.

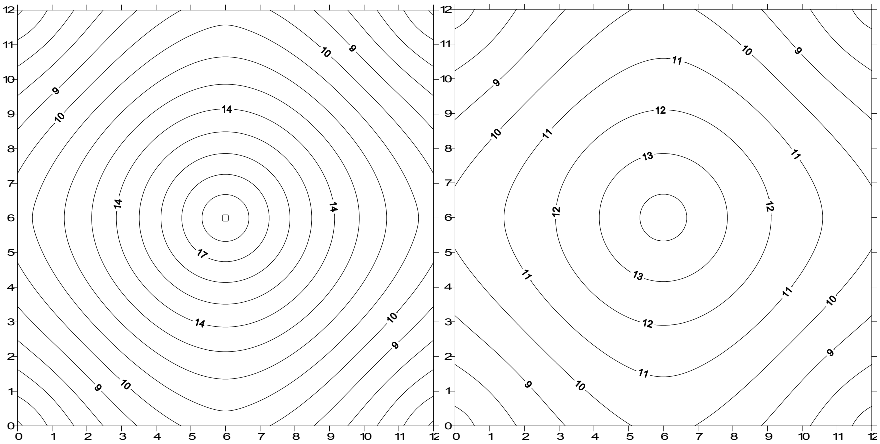


Figure 4. Settlement basin for the model with discretized masonry (a) without considering the soil-structure interaction and (b) with the interaction.

CONCLUSIONS

The following conclusions are listed:

(i) The model with discretized masonry, closer to reality, provides greater rigidity to the superstructure.

(ii) The results of the model with discretized masonry are similar to those of the model without masonry, that is, when considering the soil-structure interaction, a redistribution of efforts in the structural elements was observed.

(iii) The peripheral pillars showed an increase in load while the central pillar showed a relief in load.

(iv) A tendency towards uniformity of differential settlements was observed, especially in the model with discretized masonry. That is, the masonry contributed to greater uniformity of the settlements.

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

(vi) From the present study, the importance of more refined computational models can be seen and, in cases where settlements are significant, the effect of soil-structure interaction is relevant in the project, not only of the foundations, but also of the structure.

REFERENCES

[1] Associação Brasileira de Normas Técnicas (2022). NBR 6122. *Projeto e Execução de Fundações*. Rio de Janeiro.

[2] Meyerhof, G.G. (1953) Some Recent Foundation Research and its Application to Design. Structural Engineering, v. 31, pp. 151-167, Londres.

[3] Chamecki, S. (1954) Consideração da Rigidez da Estrutura no Cálculo dos Recalques da Fundação. In: I Congresso Brasileiro de Mecânica dos Solos e Engenharia de Fundações, v. 1, pp. 35-80, Porto Alegre.

[4] Goschy, B. (1978) Soil-Foundation-Structure Interaction. Journal of the Structural Division, ASCE, v. 104, n. ST5, pp. 749-761.

[5] Aoki, N. (1989) Discussion to Session 14, Proceedings, 12th ICSMFE, v. 5, pp. 2963-2966, Rio de Janeiro.

[6] 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.

[7] 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.

[8] SAP 2000 (2015) CSI Analysis Reference Manual v.15.0. Computers and Structures Inc., California, USA, 415 p.

[9] Poulos, H.G. & Davis, E.H. (1980) Pile Foundation Analysis and Design. New York: Wiley.

[10] Mindlin, R.D. (1936) Force at a Point in the Interior of a Semi-infinite Solid. Physics, v. 7.