Evaluation of the influence of masonry walls on the soil-structure interaction mechanism through computational modeling of a reinforced concrete building

Mariana L. A. Costa[1], Juliane C. Gonçalves[1]

[1]*Dept. of Structural Engineering, University of Juiz de Fora*
José Lourenço Kelmer Street, 36036-330, MG/Juiz de Fora, Brazil
mariana.antunes@engenharia.ufjf.br, juliane.goncalves@ufjf.br

Abstract. This work aims to investigate the influence of masonry walls on the soil-structure interaction mechanism for a reinforced concrete building. Two finite element models were developed: (i) a three-dimensional model without discretized masonry walls (the model incorporated the self-weight of the masonry walls as distributed load where the walls are located) and (ii) a model with discretized masonry walls. The latter, closer to reality, provides greater stiffness in the superstructure. The analyses employ both fixed and spring supports. When considering soil-structure interaction, a redistribution of forces in the structural elements was observed. The peripheral columns showed an increase in demand, while the central column experienced relief. A tendency towards the uniformity of differential settlements was observed, especially in the model with discretized masonry walls. Additionally, there was an increase in positive bending moments in the spans and negative bending moments at the peripheral supports of the central beam at the ground level. In other words, if the structural design does not account for settlements (as in a design without considering soil-structure interaction), these settlements, by producing a bending moment diagram different from one anticipated, can lead to localized plasticity in the beams. Thus, the importance of refined models is clear, and in cases where settlements are significant, the effect of soil-structure interaction is relevant in the design.

Keywords: masonry walls, soil-structure interaction, reinforced concrete.

1 Introduction

The consideration of soil-structure interaction is increasingly being incorporated into the practice of structural design by structural and foundation engineering firms. Recently, the latest version of ABNT NBR 6122 [1], in its item 5.5, establishes that "in structures where the deformability of foundations can influence the distribution of forces, soil-structure interaction must be studied." This recommendation from the Brazilian standard further emphasizes the importance of taking soil-structure interaction into account in the design process.

There are several works that contribute to the topic of soil-structure interaction, with the pioneering contributions of Meyerhof [2], Chamecki [3], and Goschy [4] being noteworthy. More recent works are available, but the majority focus on dynamic effects, particularly those arising from earthquakes, rather than on more practical and everyday aspects for structural and geotechnical designers.

Aoki [5] and [6] proposed a simple model for isolated vertical load transfer to soil mass and subsequently for cases of pile groups and interconnected block groups by the superstructure. For the calculation of structures considering soil-structure interaction, the following procedure was suggested: initially, the structural engineer calculates the demands on the columns assuming that the foundations are immovable. Based on these demands, the foundation engineer estimates settlements assuming that the structure's stiffness is zero, obtaining the settlement basin. The structural engineer divides the demands by the settlements and obtains initial spring coefficients at each column, then recalculates the demands on the columns considering the structure on elastic supports. From these new demands, the foundation engineer recalculates the settlements assuming that the structure's stiffness is zero, obtaining a new settlement basin. The structural engineer reassesses the new spring coefficients based on this new settlement basin, recalculates the demands, and sends them to the geotechnical engineer. The process is iterative until the desired convergence is achieved. The aforementioned procedure is only valid for the linear elastic behavior of soil, which is a valid approximation only for sandy soils. In the case of clayey soils, the same procedure is valid, but settlement estimation involves a soil model that considers not only the settlement value but also its velocity, which is related to the soil's consolidation coefficient.

Gusmão [7] mentions that one of the effects caused by soil-structure interaction is a redistribution of forces in structural elements, especially the demands on columns. It is also noted that theoretical analyses and real case studies confirm the importance of soil-structure interaction in building projects, which can lead to more economical and safer designs.

It is within this context that this work is situated. The influence of masonry walls on the soil-structure interaction mechanism for a reinforced concrete building is studied. To do so, two finite element models are developed using the commercial structural analysis program SAP2000 (version 15) [8]: (i) a three-dimensional model without discretized masonry walls (the model incorporated the self-weight of the masonry walls as distributed load where the walls are located) and (ii) a three-dimensional model with discretized masonry walls. The analyses employ both immovable supports and spring supports. The stiffness coefficients of the spring supports are defined based on the relationship between the normal force on the support and the estimated settlement through the proposal of Poulos and Davis [9].

2 Characteristics of the building and its foundations

The building under study is made of reinforced concrete and has four floors. The floor height is consistent throughout, measuring three meters. The building has double symmetry, and the floor plan is shown in Fig. 1.

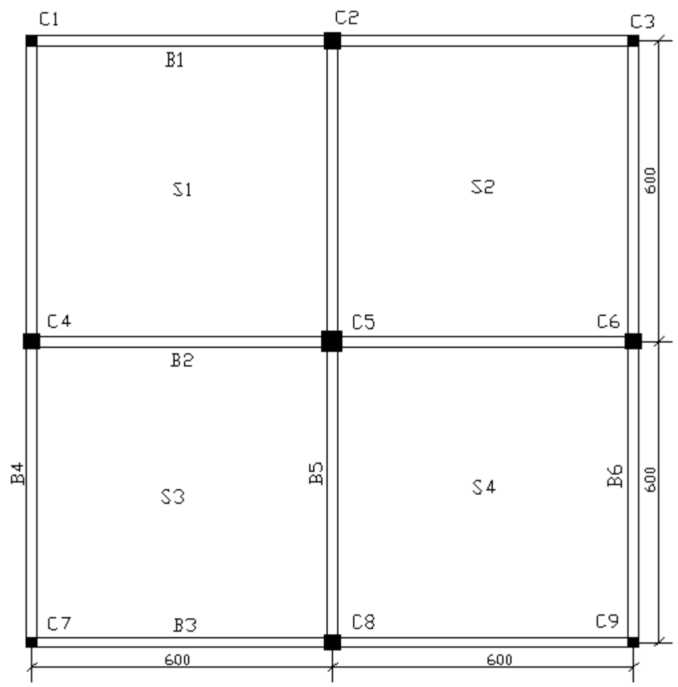


Figure 1. Floor plan of the building (measurements in centimeters)

Figure 1 shows that the building has 9 columns reaching down to the foundations. Columns C1, C3, C7, and

C9 have a cross-sectional area of 20 x 20 centimeters. Columns C2, C4, C6, and C8 have a cross-sectional area of 30 x 30 centimeters, and column C5 has an area of 40 x 40 centimeters. All beams have a cross-sectional area of 20 x 80 centimeters, and the slabs have a height of 10 centimeters.

The loads come from the self-weight of the structure and a live load on the slabs of 3 kN/m². The material properties of the superstructure (slabs, beams, and columns) are f_{ck} = 25 MPa for concrete, a unit weight of 25 kN/m³, modulus of elasticity E = 248000 MPa, and Poisson's ratio of 0.2.

Regarding the masonry walls, since the building is low-rise (four floors), meaning it does not require elements with high resistance to stresses, such as concrete blocks, ceramic blocks were chosen. Thus, the masonry walls are assumed to have a thickness of 15 centimeters, a specific weight of 16 kN/m³, and a modulus of elasticity $E_{masonry} = 4000$ MPa.

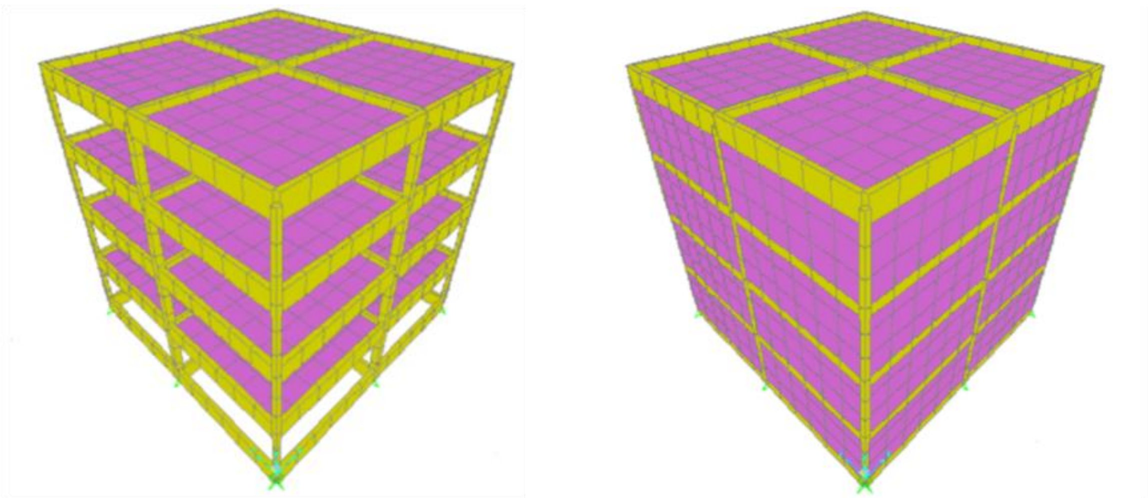
The foundations consist of precast concrete piles (isolated) with diameters of 30, 40, and 60 centimeters, driven 14 meters (L) into a thick layer of loosely compacted sand (E = 9 MPa and ν = 0.2).

3 Computational modeling of the reinforced concrete building

The structure was discretized into finite elements using the commercial structural analysis program SAP2000 (Version 15). Beam elements were used for the beams and columns, and shell elements were used for the slabs. Two models were developed: the first model incorporated the self-weight of the masonry walls as distributed load where the walls are located (7.2 kN/m), and the second model had the masonry walls discretized into shell elements.

Figure 2(a) illustrates the three-dimensional model without discretized masonry walls (masonry walls incorporated as distributed load), and Figure 2(b) shows the model with discretized masonry walls.

Figure 3 details a part of the structure with the self-weight of the masonry walls incorporated as distributed load.



(a) (b)

Figure 2. (a) Three-dimensional model of the building without discretized masonry walls (masonry walls incorporated as distributed load) and (b) Model with discretized masonry walls

For the analyses, fixed supports and spring supports are employed. The stiffness coefficients of the supports (K) are defined using eq. (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 [9].

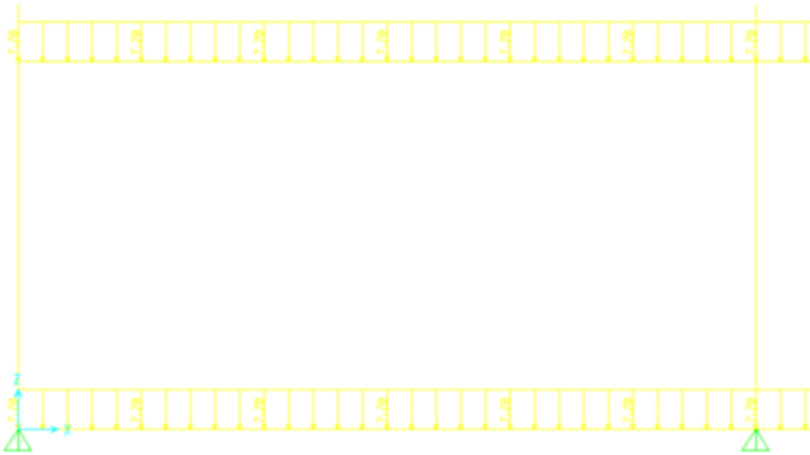


Figure 3. Detail of a part of the structure with the self-weight of the masonry incorporated as distributed load

4 Poulos and Davis model for pile settlement estimation

Poulos and Davis [9] introduced a rational method for estimating pile settlements based on numerical procedures that employ Mindlin's equations [10]. The method, presented in the form of charts, allows for the prediction of settlement of an individual pile, initially assumed to be incompressible, in a semi-infinite, homogeneous elastic medium. Subsequently, corrective factors were developed to account for the influence of pile compressibility, the presence of a considered rigid (or immovable) boundary, the Poisson's ratio, and soil improvement at the base level. For a pile with diameter or width B, embedded in a medium with Young's modulus E, loaded (in compression) by Q_0 at its top, the settlement at the top is given by eq. (2):

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

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

$$I = I_0 R_k R_h R_\nu R_b. \quad (3)$$

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

5 Results and discussions

Table 1 shows the corrective values used in the Poulos and Davis model.

Table 1. Corrective factors in the Poulos and Davis model

Column	Pile diameter (m)	L/B	I_0	R_k	R_v	I
C1	0,3	46,7	0,047	1,15	0,85	0,04594
C2	0,4	35,0	0,058	1,10	0,85	0,05423
C5	0,6	23,3	0,080	1,08	0,85	0,07344

Table 2 presents the normal force values obtained in the columns, without considering the soil-structure interaction and with the interaction, for the structural model without discretized masonry walls (masonry walls incorporated as distributed load). Table 3 presents the normal force values obtained in the columns, without considering the soil-structure interaction and with the interaction, for the structural model with masonry walls discretized into finite elements.

Table 2. Normal forces obtained in the columns, without considering the soil-structure interaction and with the interaction, for the model without discretized masonry walls (masonry walls incorporated as distributed load)

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	3,5	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

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

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

Table 3. Normal forces obtained in the columns, without considering the soil-structure interaction and with the interaction, for the model with discretized masonry walls

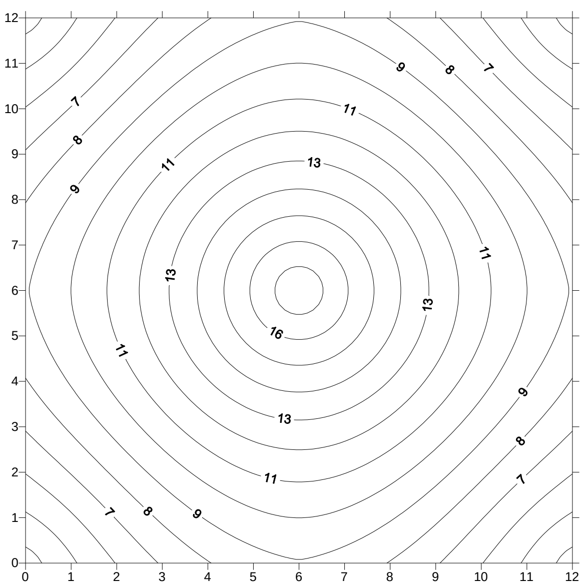
Column	Without interaction				With interaction		Difference (%)	
	Load (kN)	Settlement SD*	Settlement GD*	k = Q/w (kN/m)	Load (kN)	Settlement (mm)	Load	Settlement **
C1	282	0	4,8	58750	384	6,51	36	36
C2	705	0	10,6	66509	685	10,3	-3	-3
C5	1414	0	19,2	73646	1076	14,6	-24	-24

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

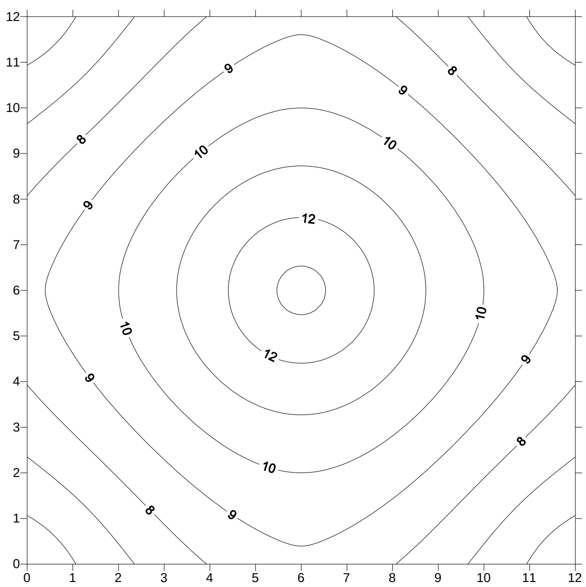
** Difference from the forecast in the initial geotechnical design (without interaction).

Table 2 shows that in the second analysis, with movable supports (with values of k), new loads and settlements were produced (since the analysis is linear, the variations in loads and settlements are naturally the same). The peripheral columns had their loads increased (a difference of 44%), while the internal column had its load decreased (a difference of 25%), as reported by Gusmão [7], indicating a redistribution of forces in the columns. The same behavior is observed in Tab. 3, which presents a more refined model (closer to reality) with the discretization of masonry walls. The introduction of masonry walls in the model represents an increase in the stiffness of the superstructure. An increase in load of approximately 36% was noticed in the peripheral columns and a relief of 24% in the central column.

Figure 4 shows the settlement basin without considering the soil-structure interaction and considering it for the model without discretized masonry walls (masonry walls incorporated as distributed load). Meanwhile, Fig. 5 illustrates the settlement basin without considering the soil-structure interaction and considering it for the model with discretized masonry walls.



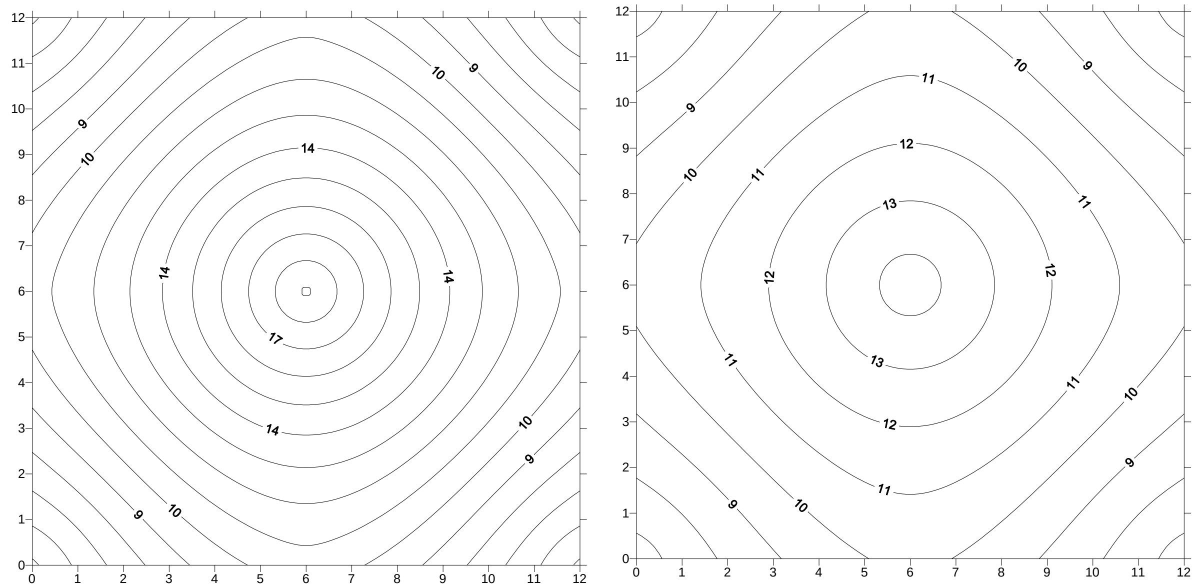
(a)



(b)

Figure 4. Settlement basin for the model without discretized masonry walls (masonry walls incorporated as

distributed load) (a) without considering the soil-structure interaction and (b) with the interaction



(a) (b)

Figure 5. Settlement basin for the model with discretized masonry walls (a) without considering the soil-structure interaction and (b) with the interaction

In Fig. 4 and Fig. 5, the effect of soil-structure interaction is observed, showing a tendency towards uniform settlement. The discretization of masonry walls further contributes to greater uniformity in the distribution of settlement differentials.

Figure 6 illustrates the bending moment diagrams of the lower central beam (ground floor) for the model with discretized masonry walls (closer to reality) for the two analyzed situations, namely, without considering soil-structure interaction and with interaction. This beam was selected because the bottom belts and beams are the ones most affected by settlements.

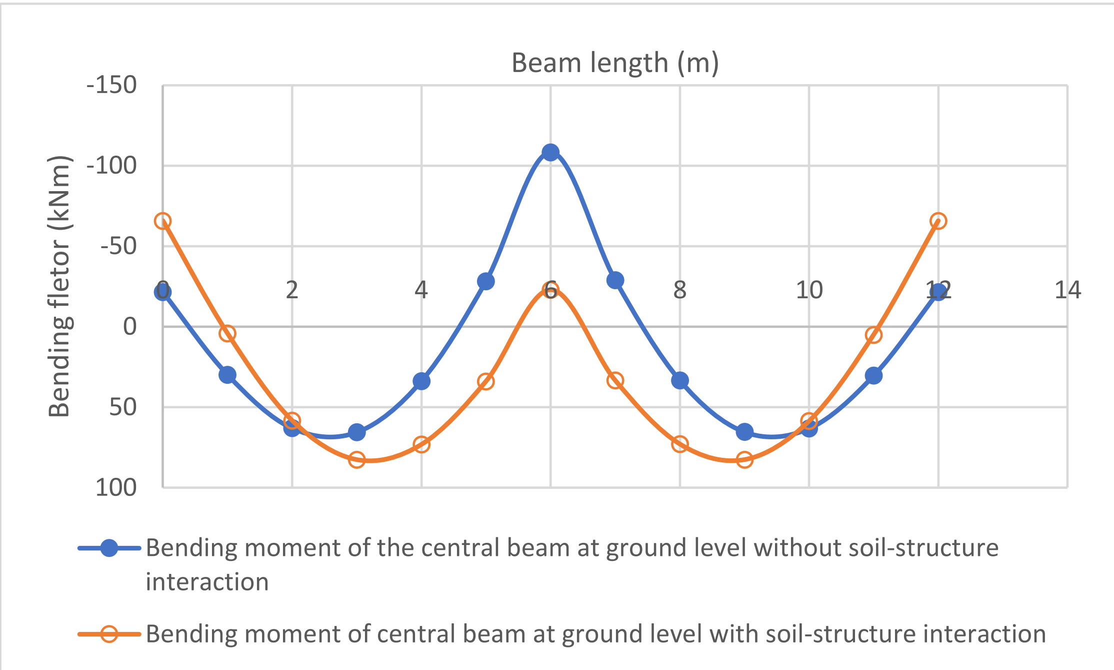


Figure 6. Bending moment diagram of the central beam at ground level, without considering soil-structure interaction and with interaction

Figure 6 shows an increase in positive bending moments in the spans (around 20% difference) and a considerable increase in negative bending moments at peripheral supports (approximately 67% difference). In practice, if the structural design does not consider settlements (as in the case of a design without soil-structure interaction), settlements, by producing a different bending moment diagram than expected, can lead to localized yielding in the beams.

It is evident that in cases where settlements are significant, the effect of soil-structure interaction is important in both foundation and structural design. There are reports of buildings in Santos that have experienced significant settlements, leading to crushing of peripheral columns and intense cracking of the first levels of beams.

6 Conclusions

The following conclusions are enumerated:

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

(ii) The results of the model with discretized masonry walls are similar those of the model without discretized masonry walls (masonry walls incorporated as distributed load); that is, when considering soil-structure interaction, a redistribution of forces in the structural elements was observed. It is worth noting that a tendency toward uniformity in differential settlements, especially in the model with discretized masonry, was observed. In other words, the masonry walls contributed to greater uniformity in the settlements.

(iii) Peripheral columns showed an increase in demand while the central column exhibited a relief of demand.

(iv) An increase in positive moments in spans and negative moments at peripheral supports of the central beam at ground level was observed. Thus, if the structural design does not consider settlements (as in the case of a design without soil-structure interaction), settlements, by producing a bending moment diagram different from the expected, can lead to localized yielding in the beams.

(v) This study shows the importance of more refined computational models, and in cases where settlements are significant, the effect of soil-structure interaction is relevant not only in the design of foundations but also in the structure itself.

(vi) It is noted that further investigations are needed regarding the influence of masonry walls in taller buildings, as this would allow determining at what point the observed effects become practically relevant, providing more actionable insights for engineers.

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