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STRESS ANALYSIS IN FOUNDATION ELEMENTS USING SOIL-STRUCTURE INTERACTION

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Abstract. In the structural building design, it is usually considered the structure supported on a rigid surface, which does not occur in real situations. It is necessary to analyze the soil deformations to perform a structural determination closer to actual behavior. This work had as objective to analyze the vertical and horizontal stresses of footing and pile cap subjected to normal force of compression. It modeled with software that uses as a basis the Finite Element Method. It was analyzed in the footing with fixed supports, that the loads imposed migrate to the supports just below the perimeter of the column, without significant distribution and the strut-and-tie model was not verified. Therefore, the foundations model on rigid supports does not satisfactorily represent the actual stresses behavior on the element. In the footing supported on spring elements, more excellent distribution of the vertical compressive stresses and the formation of tension and compression areas next to the column can be observed in horizontal stresses analysis, describing the theoretical strut-and-tie model. The soil-structure interaction analysis in the pile cap did not modify the stress behavior due to being supported as non-deformable or in soil with high resistance. As usually are the supporting layers of piles, with the soil spring stiffness coefficient high, considered as rigid. Therefore, the use of flexible supports made it possible to analyze the stresses in the footing in an approximate way of real behavior, as observed in the literature.

Keywords: Footing. FEM. Pile cap. Structural modeling

1 Introduction

For the structural building design, it is necessary to determine all acting forces to calculate each constituent element of the structural system. The loads are resisted by the slabs, beams, and columns, which migrate to the foundations, transmitting them to the ground. The soil does not behave homogeneously, because it deforms when receiving the requests, causing a disturbance in the load's flow and, consequently, an element's stresses redistribution. The structural systems of civil engineering works have three types, the superstructure (slabs, beams, and columns), infrastructure (structural elements of foundation), and the mass of soil [1]. These elements interact with each other, transferring the forces produced in the superstructure to the foundation and then to geotechnical mass. Thus, the structural performance of a building depends on the interaction between these elements.
In building projects, it is usual to consider the supports as undeformable. However, this simplification can show an unrealistic distribution of loads, because when the soil is requested, it deforms and causes

a redistribution of stresses in the structural elements. This redistribution can cause fissures in the superstructure that was not designed to support these new loads [2].

The Soil-Structure Interaction (SSI) is a combined analysis of the structural and the geotechnical systems, which considers the displacement of the foundation elements, providing rearrangement of the loads in the structural elements [3]. SSI is a structural analysis method that considers the deformable soil, therefore allow an optimized structure design. This analysis requires sophisticated numerical methods, and a large number of calculations, which manually performing is impossible. The Finite Element Method (FEM) is a problem-solving technique that correlates a system of algebraic equations to a variable searched for a finite number of points [4]. This technique is widely used in the determination of structures considering the Soil-Structure Interaction, and it considers the soil as not rigid. It is admitting the soil's deformability as springs, with a coefficient of stiffness calculated by compressing the soil under the foundation elements.

Therefore, the popularization of microcomputers, coupled with the evolution of theories on the behavior of structures, there was a significant advance in understanding how the soil interacts with specific situations. It can perform more sophisticated calculations and apply variables closer to reality.

2 Methodology

In this work were used loads as per the NBR 6120 (ABNT, 1980) to estimate the actions in the columns. However, as the focus of this work is the stress behavior in the foundations' elements, the superstructure loads were reckoned.

The calculation of the load capacity and the settlement of the foundation were determined by the method presented by [5]. It used three Standard Penetration Test (SPT) result samples, two clay soils, and one sandy, which provided the soil layer thickness, type, and N_{SPT} (number of strokes required to pierce the last 30 centimeters of each one-meter layer).

With the allowable soil strength and the load applied by the column, the footing area dimension can be calculated by Equation 1.

$$A_{sap} = \frac{1{,}05\,.N_d}{\sigma_{adm}} \tag{1}$$

For the sandy soil profile and one of the clay soils, were determined square and rectangular isolated footing foundations, and a pile cap for the other clay soil, because the first soil layers did not have adequate resistance.

The displacements were calculated based on the methodology of [5] for the shallow and deep foundations, verifying if they are within the allowable limits. Defined the load (P) that the column will transmit and calculated the displacement (d), the vertical reaction coefficient (kv) is determined, it is the value that represents the ground stiffness when compressed by the pressure imposed, as described in Equation 2.

$$P = k_v\,.d \tag{2}$$

The Finite Element program SAP2000 (COMPUTERS AND STRUCTURES, 2011) used in this work performed eight models of foundation elements, two types of rigid footing, square and rectangular, for the clay and sandy soil each. With the two different types of rigid footing models, it is analyzed the difference in the intensity of the bending moment produced by the lever arm in the rectangular footing to the square one.

For the low strength clay soil in the first layers, a foundation was modeled considering rigid supports and another with spring elements. A pile cap was adopted, and the principal stresses acting will be analyzed.

Figure 1 shows the fixed and flexible supports in the footing type foundation.

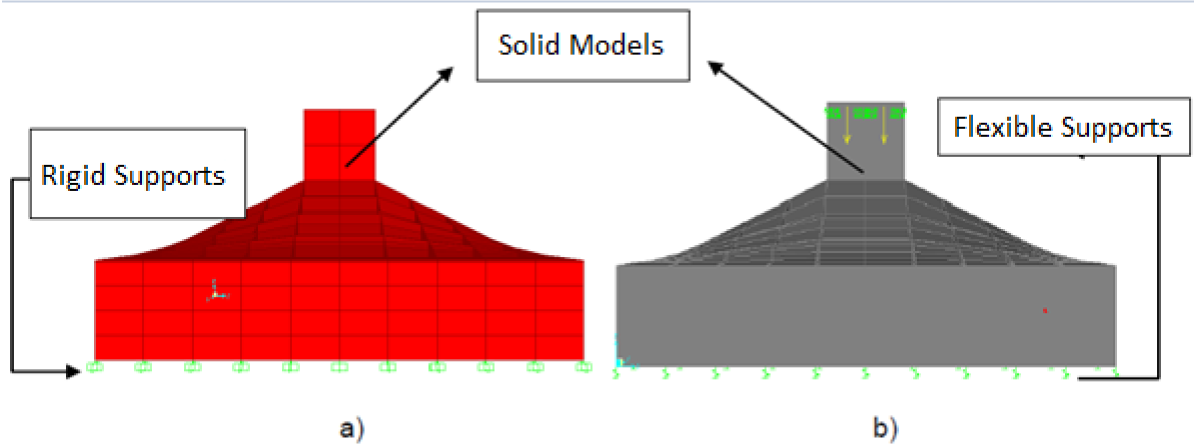

Figure 1. Rectangular footing. a) On rigid supports b) On springs

For the modeling of the foundation, were used solid finite elements, that have eight nodes and three degrees of freedom at each node. They based on the isoparametric formulation, which includes nine bending modes and has its local coordinate system, thus providing a closer approximation of a real result.

The behavior of the stresses in the foundation elements was analyzed considering it as a solid element and the soil as undeformable. It was compared with the model that considers the hypothesis that the soil is compressible (SSI), simulating its behavior through springs with a deformability coefficient equal to the soil stiffness coefficient.

The characteristics of the material that consists of the foundation elements analyzed are in Table 1.

Table 1. Coefficients in constitutive relations

f_{ck} (kN/m²)	Elastic modulus E_{cs} (kN/m²)	γ (kN/m³)	Poisson's ratio
20.000	21.000.000	25	0,2

Source: The Author

3 Results

3.1 Loads

The column support reaction was determined with live and dead loads, considering the influence area of each one. It used the specific gravity of the materials described in [6] and force design coefficients of [7]. Table 2 shows the result of the normal force in the column under study.

Table 2: Accumulated load along the column.

Normal effort (kN)
772,14

Source: The Author

3.2 Calculation of load capacity

Table 3 contains the results of the allowable stresses with their soil types, analyzed using the SPT test.

Table 3. Allowable soil bearing capacity

Soil Type	Failure Mode	Foundation Type	σ_{allow} (MPa)
Medium-fine sand, medium compact	Local	Square	0,24
		Rectangular	0,34
Clay with sand, hard	General	Square	0,40
		Rectangular	0,40
Clay with organic matter	Punching	Pile cap	0,40

Source: The Author

3.3 Calculation of initial absolute displacement and the spring element stiffness coefficients

The calculations of the displacement and the stiffness coefficient of the spring element were by the method presented by [5], considering the type of foundation and soil. Table 4 shows the calculated settlements with their soil and foundation types. The stiffness coefficients are tabulated, determined in each situation.

Table 4. Absolute initial displacement, limits and stiffness coefficient

Soil Type	Foundation Type	ρ (mm)	ρ_{lim} (mm)	Kz (kN/m)
Medium-fine sand, medium compact	Square	12,30	17,77	15.160
	Rectangular	13,70	17,77	27.900
Clay with sand, hard	Square	9,00		37.800
	Rectangular	11,20	23,45	47.600
Clay with organic matter	Pile cap	3,05	23,45	3.164.508

Source: The Author

3.4 Sizing of foundation elements

With the allowable soil bearing capacity values and the stress value imposed by the column, the dimension of the footing area can be calculated using Equation 1.

$$A_{sap} = \frac{1{,}05 \, .N_d}{\sigma_{adm}} \quad (1)$$

Table 5 shows the dimensions of the foundation elements calculated and adopted for the present study.

Table 5. Dimensions of the foundations

Soil Type	Foundation Type	Side B (m)	Side A (m)	Height (m)
1- Medium-fine sand, medium compact	Square	1,70	1,70	0,60
	Rectangular	0,34	2,00	0,70
2- Clay with sand, hard	Square	0,40	1,50	0,60
	Rectangular	0,40	2,00	0,70
3- Clay with organic matter	Pile cap	0,50	1,50	0,60

Source: The Author

3.5 Soil-Structure Interaction Analysis in SAP2000

Figure 2 shows the behavior of the vertical stresses in the square footing from the compression loads imposed by the column. These transfer to the base of the ground by 121 supports, which prevent displacement (rigid), evenly distributed over an area of 2.25 m².

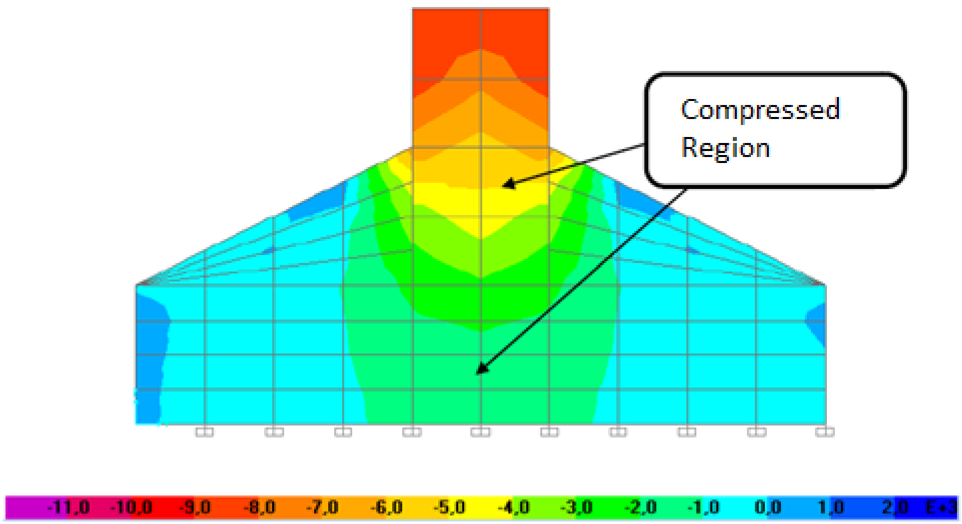

Figure 2. Vertical stresses acting on the footing with fixed supports (kN/m²)

Figure 2 presents the loads migrate to the supports just below the column perimeter, therefore having a smaller compression distribution across the footing area.

Figure 3 shows the horizontal stresses acting on the footing. With rigid supports no tensile stresses are recorded at the base, and there are small compression zones due to the support reactions of the area center.

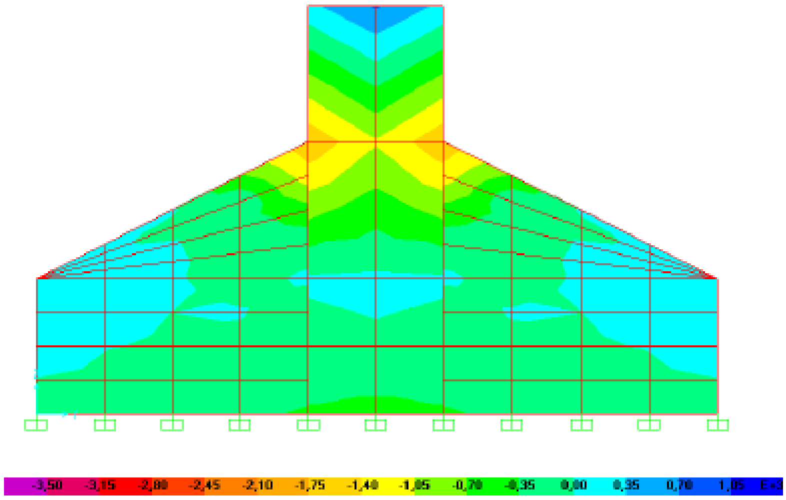

Figure 3. Horizontal stresses acting on the footing with fixed supports (kN/m²)

Figure 4 presents the behavior of maximum moments acting on the rigid footing. With the rigid supports, the foundation showed a negative bending moment in the center of the base area; accordingly, there is a tendency for the element to flex upwards. The dashed lines in Figure 4 show the bending moment acting on the foundation element.

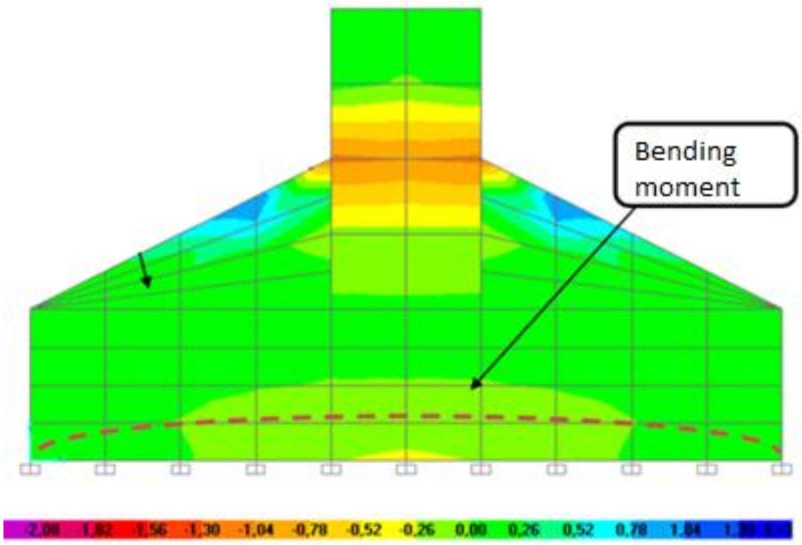

Figure 4. Bending moment acting on the footing with fixed supports (kN.m)

Figure 5 shows the behavior of square footing stresses in the soil type 2 (clay with sand) where the supports are replaced by springs, simulating soil deformation in all contact areas. It has shown the compressed regions indicated by the contour of the stresses that there is a better distribution.

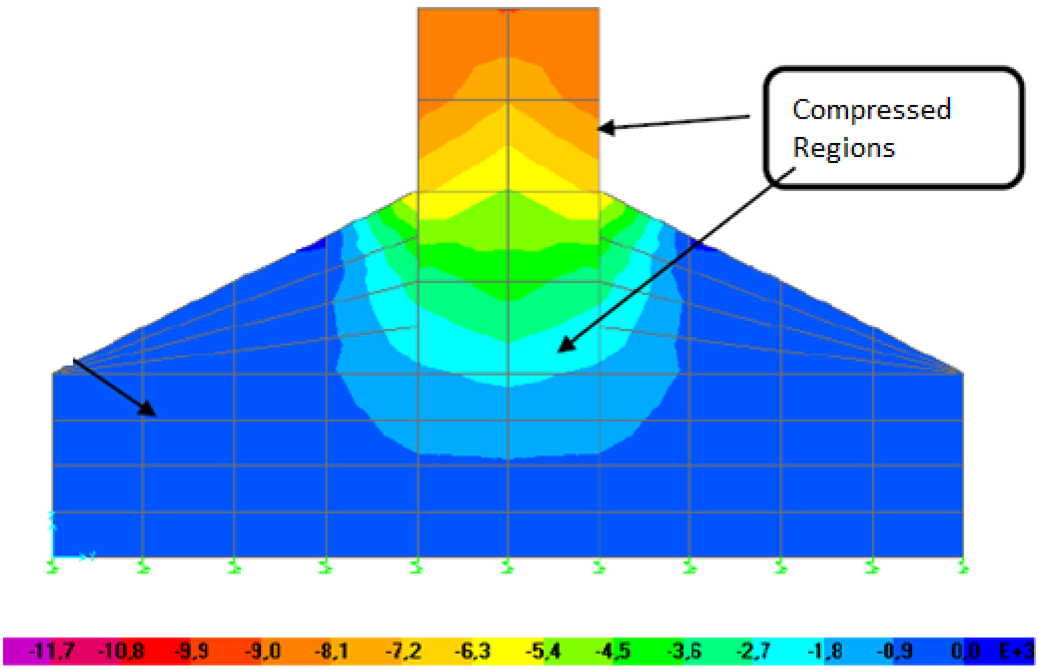

Figure 5. Vertical stresses acting on the shoe with flexible supports (kN/m²)

In this configuration there is a more excellent distribution of stresses coming from the column by the element to the ground and, compared to Figure 2, shows the closest behavior of the actual situation of the efforts on the footing.

Figure 6 presents the horizontal stresses acting on the foundation with flexible supports. In the image, it is illustrated the tensile tensions work on the footing base and compression near the column. When associated with the behaviors shown in Figures 2 and 3, it is remarkable the approximation with the real act of tensions.

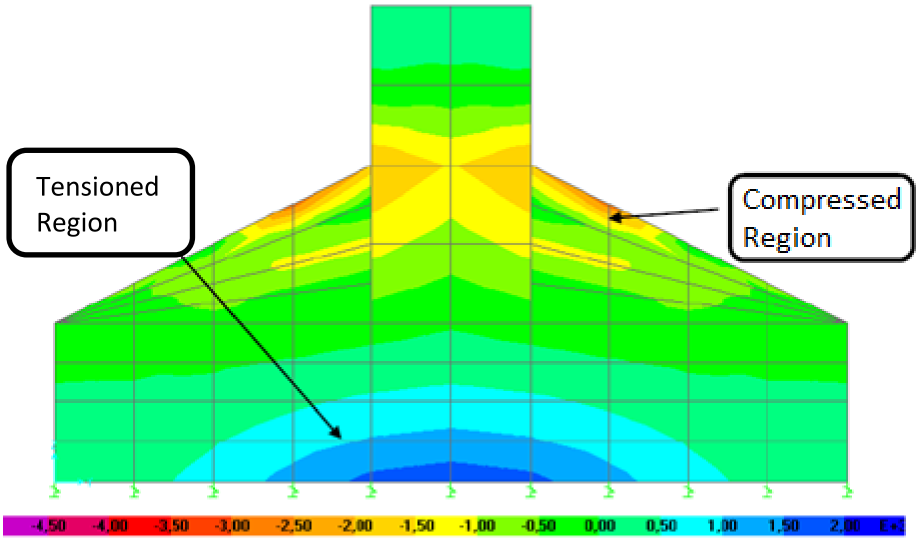

Figure 6. Horizontal stresses acting on the shoe with flexible supports (kN / m²)

In Figure 7, the behavior of the maximum moments acting on the rigid footing with springs is different from the shown in Figure 4. It indicates a positive bending moment in the base center. The dashed line shows the direction of bending moment or deformation in the center of the foundation.

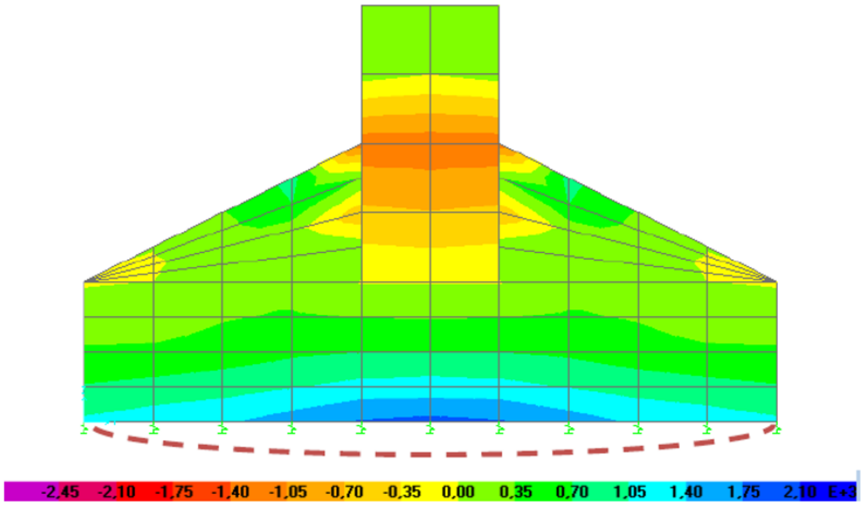

Figure 7. Bending moment acting on the footing with flexible supports (kN.m)

The results found for the rectangular footing presented the same behaviors of the square one, but with more significant intensities. There was a better distribution of vertical stress with the increase of the contact surface, which also caused higher horizontal stress and bending moment, with the rise of the footing toe width. With the soil type change to a more compressible one, there was a 14.3% and 12.5% increase in the horizontal stresses and bending moment in the center of the foundation base, respectively. As the soil is more deformable, the springs compress further at the center than at the edges.

In the pile cap, there were no stress changes due to Soil-Structure Interaction. It is because the stiffness coefficient is high at the base of the pile, acting as rigid supports. However, it was possible to visualize the strut-and-tie model (Figures 8 and 9), where the load from the column goes towards the piles, causing traction between them.

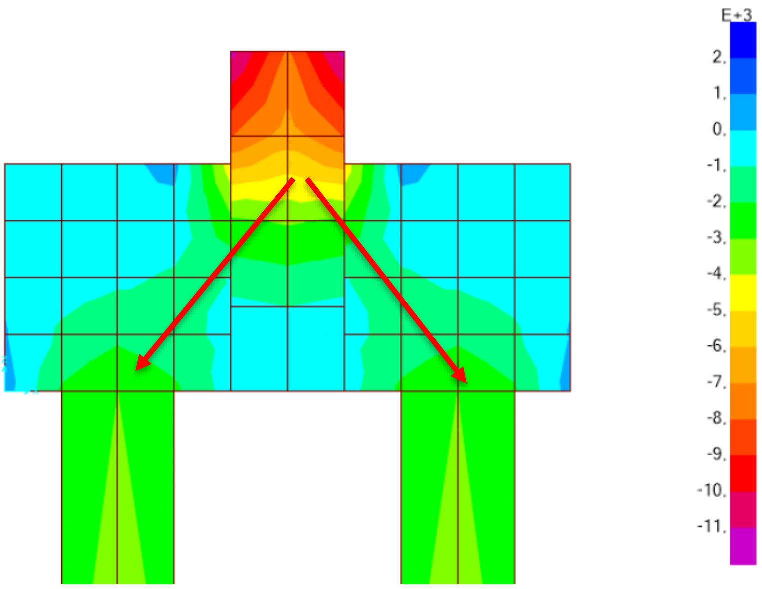

Figure 8. Vertical stresses acting on the crowning block (kN / m²)

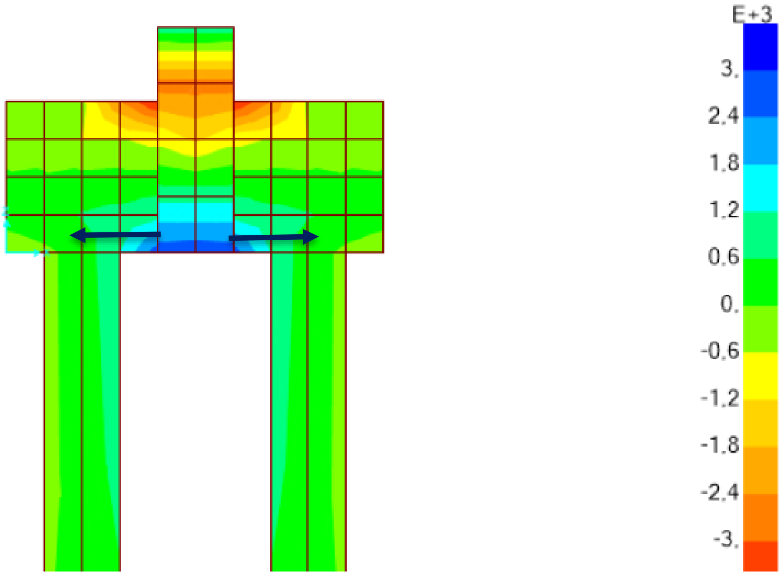

Figure 9. Horizontal stresses acting on the pile cap (kN / m²)

4 Conclusions

Initially, considering footings with rigid supports, the loads imposed on the foundation migrate to the supports just below the perimeter of the column, without even distribution across the base. On the fixed supports was not verified the appearance of horizontal stresses of tension and compression, as devised by the strut-and-tie method. In the bending moment analysis, a negative bending moment concentration was found in the center of the footing. Therefore, the foundation model on the rigid supports does not satisfactorily represent the behavior of the actual stresses in the element, due to the lack of stress distribution and consequently without lever arm and bending moment.

For footing with spring support, a more excellent compression stress distribution can be seen toward the base in the vertical plane. It was verified the formation of traction in the bottom and compression near the column. When the stresses in the horizontal plane were also analyzed, the two situations describe the strut-and-tie method. In the bending moment analysis, different behavior can be seen than with fixed supports, finding a positive bending moment concentration in the base. At the rectangular footing analysis in the change of the soil type to a more compressible, there was a 14.3% and 12.5% increase in the horizontal stresses and bending moment in the center of the foundation base, respectively.

The analysis in the pile cap did not change the stress behavior with SSI consideration, because the layer that supports the piles have a high strength soil, making the soil stiffness coefficient high and considered as rigid. With the use of fixed supports, it was possible to analyze the stresses acting on the foundation so that it was closer to the behavior of the strut-and-tie model.

At the end of this analysis, stress behavior was found to be closer to reality in footing models with flexible supports and, with the pile cap on both supports, it shows the strut-and-tie behavior.

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