Analysis of Soil-Structure Interaction in Raft Foundation Using Grid Analogy

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Abstract. This study uses the Grid Analogy Method as a simplified approach for analyzing soil-structure interaction in raft foundations. Nowadays, structural analysis softwares plays a crucial role in achieving precise results through various methods. The Grid Analogy Method, applied numerically, treats two-dimensional plate elements as grid elements, offering an effective and relatively precise analysis. This research adapts the LAGI software, in Python, to analyze rafts on soil, enhancing its capability from slab floors to flexible structural bases. By employing the Grid Analogy, the study models soil-structure interaction, providing accurate insights into raft behavior under different loads and soil conditions. Practical applications validate this approach, comparing results with traditional and consolidated structural analysis software. Internal force diagrams highlight maximum bending moments and displacements, emphasizing the method's effectiveness and innovation in structural engineering.

Keywords: Grid Analogy; Soil-Structure Interaction; Python; Raft Foundation.

1 Introduction

In the context of Civil Engineering, projects are of indisputable importance, and according to Silva [1], foundation design, specifically, requires special care, as these structures are responsible for transmitting the building's loads to the supporting soil. The study of soil resistance and the proper sizing of foundations are key elements to ensure the safety of the structure.

In this context, it is stated, based on Ortega and Pedreiro [2], that well-designed and executed foundations can account for 3% to 10% of the total cost of a building, whereas poor design of these structural elements can lead to costs five to ten times higher than ideal execution due to the need for corrections. Additionally, it is important to emphasize that foundation structures represent a significant part of the building as a whole.

The Brazilian standard NBR 6122 [3] defines the raft as a shallow foundation that supports all distributed loads or those coming from the columns of a structure. The standard NBR 6118 [4] classifies the raft -type structure as a slab, that is, a structural element where two of its dimensions are larger than the third, and it also receives loads perpendicular to its main surface. As a structural element, the raft acts as a load distribution base, transferring the efforts from the superstructure (slabs, beams, and columns) to the soil.

The Grid Analogy, a technique used by Marcus in 1932, according to Timoshenko et al. [5], allows for the analysis of plate elements by replacing them with an equivalent grid, which is a composition of beams where distributed and concentrated loads are applied to the nodes or bars.

The main objective of this work is to analyze the interaction between the soil and raft -type foundations using the grid analogy methodology. To this end, the LAGI software was adapted to simulate the behavior of slabs supported on flexible bases, representing the foundations placed on the soil. The adaptation allowed for the analysis and graphical visualization of the forces acting on the foundation in contact with the soil, as well as the deformed surface of the raft, enriching the understanding of the structure's behavior.

2 Raft foundation

The Brazilian standard NBR 6122 [3] defines the raft foundation as a shallow foundation element with sufficient stiffness to support and distribute more than 70% of the structure's loads. According to Doria [6], the raft is a shallow foundation made of reinforced or prestressed concrete, capable of uniformly distributing loads from columns and masonry to the soil. It is generally used in soils with low load-bearing capacity to equalize settlements, or when strip footings are very close together or cover more than half of the construction area. Velloso and Lopes [7] describe the raft as a shallow foundation that transfers the building's loads to a concrete slab.

Rafts are classified according to three main criteria. First, in terms of geometry, they can be flat, with pedestals or mushrooms, ribbed, or box-shaped. Regarding flexural stiffness, rafts are classified as rigid, with high resistance, or elastic, with lower stiffness and larger displacements. In terms of technology, they can be made of reinforced concrete, which requires greater thickness to support loads, or prestressed concrete, with an ideal thickness approximately 70% of that required for reinforced concrete. The choice of concrete should consider durability and strength, according to NBR 6118 [4].

3 Soil-structure interaction and the Winkler Hypothesis

The soil-structure interaction, initiated by Meyerhof [8] and Chamecki [9], analyzes the displacements and internal forces of structures in contact with the soil. The study involves evaluating contact pressures and determining coefficients based on tests.

The method proposed by Winkler, as cited by Stramandinoli [10], is one of the oldest and most popular for analyzing soil-structure interaction, providing a quick and satisfactory response for elastic foundations on soil. Initially, Winkler modeled the soil as an elastic medium to calculate stresses in railroad sleepers, later expanding the application to concrete pavements.

In Winkler's model, the soil is represented as a set of independent linear springs, with the vertical reaction coefficient being constant at all contact points of the foundation base. However, this approach simplifies reality by neglecting the interaction between adjacent springs, which can introduce errors. Additionally, soil heterogeneity can cause inaccuracies in determining the vertical reaction coefficient and in the model's responses.

4 Grid analogy

The grid analogy method, initially used due to the similarity between the behavior of plane frames and grids through the displacement method, is widely applied in plate analysis due to its efficiency and simplicity, as highlighted by Stramandinoli [10]. According to Dória [6], this method transforms a plate into an equivalent grid of bars, where each bar represents a strip of the slab, including its central axes. Barboza [11] notes that using an equivalent grid to represent a solid slab requires adjusting the bar stiffnesses to obtain results that are approximate to reality, as Hambly [12] points out that the results are only approximate due to differences in behavior between structural elements. Furthermore, creating an equivalent grid often results in a large number of nodes, bars, and high degrees of hyperstaticity, making the use of computational methods necessary for the analysis, as stated by Oliveira and Barbirato [13].

4.1 Physical and geometric properties of grids

The physical and geometric properties of the bars in an equivalent grid need to be adjusted for the accuracy of the analysis. The bars represent parts of the solid slab, so their physical and behavioral properties under loads must closely represent those of the plates. Physically, the material of the bar affects the behavior of the grid. According to Dória [6], for the reinforced concrete raft, the shear deformation modulus, G, can be defined as follows:

$$G = \frac{E}{2(1+v)} \tag{1}$$

where E is the longitudinal deformation modulus and v is the Poisson's ratio, used for isotropic materials in a plane stress state.

For the geometry of the grid elements, with width b and thickness h, the bending moments of inertia (I) and the torsion constants (J) can be calculated using the following formulas:

$$I = \frac{bh^3}{12}, \tag{2}$$

$$J = \frac{3b^3h^3}{10(b^2+h^2)}. \tag{3}$$

.

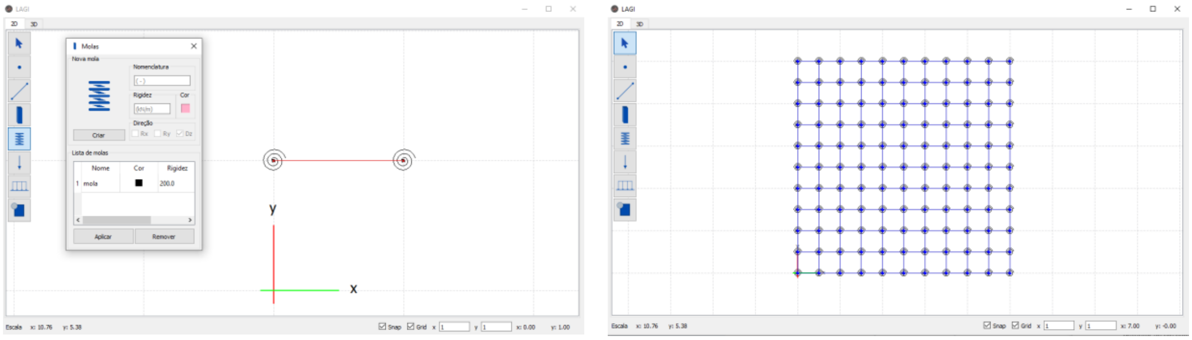
NBR 6118 [4] recommends reducing the torsional moment of inertia to 10% of the calculated elastic stiffness.

5 Computational Implementation

The computational implementation was based on adaptations made to the LAGI software (Oliveira and Barbirato [13]), which analyzes the behavior of slabs using the Grid Analogy, including beams and columns. In applying the Grid Analogy, the adjustment of beam stiffness parameters is done using standard formulas widely recommended in the technical literature. Although these parameters can be customized by users, such adjustments may result in significant variations in the final results.

To implement the Direct Stiffness Method, the bars were considered subjected to three local coordinates at each end, associated with torsion, bending, and shear forces. The bending stiffness of the columns was directly incorporated into the global stiffness matrix of the horizontal system. This incorporation included vertical bars located above and below the floor, fixed at their ends with no direct contact with the slab. These bars were subjected to two rotations and a vertical translation, which was prescribed as zero.

For the functional analysis of raft foundations, Winkler formulations were incorporated, as described by Stramandinoli [10], considering elastic supports at each node of the raft discretization. Geotechnical considerations were used to determine the vertical stiffness coefficient, suitably simulating soil contact. With the new implementation, LAGI Radier allows for the visualization of spring elements in both plan and 3D views. In processing, which uses the direct stiffness method under elastic-linear analysis, the springs are incorporated after the assembly of the global stiffness matrix, focusing on vertical displacement. The functionality to add concentrated forces at the mesh nodes was also implemented. This allows for the consideration of distributed force lines, attempting to represent the load of a wall directly on the raft. In Figure 1, the menu of LAGI Radier shows the functionality for including elastic support.



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(a)

(b)

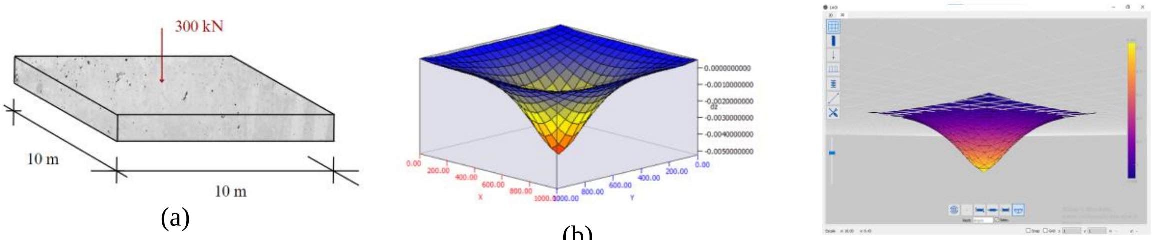
Figure 1. Interfaces: (a) Application of the spring element at a node; (b) Radier modeled in 2D.

6 Applications

To verify the effectiveness of the modifications made to the LAGI software, cases from the literature were processed, with the results presented for each application. The analysis includes cases simulated in LAGI and comparisons with results from the CALCO program (Cass [15]) and Braga [16].

6.1 Application 01

The first case analyzes a square plate with a side of 10 meters and a thickness of 15 cm supported on the ground, subjected to a point load of 300 kN at the center. The discretization mesh was set to 0.5 m, and the soil was represented with a vertical reaction coefficient of k=1000 kN/m. Concrete with a compressive strength f_{ck} of 20 MPa was considered. The model analyzed, along with the displacement responses from both CALCO and LAGI Radier, and tabulated results related to displacement behavior and maximum moment values, are shown in Fig. 2 and Tab. 1.



(a)

(b)

(c)

Figure 2. Representations: (a) Application characterization; (b) Maximum displacement – CALCO; (c) Maximum displacement – LAGI Radier.

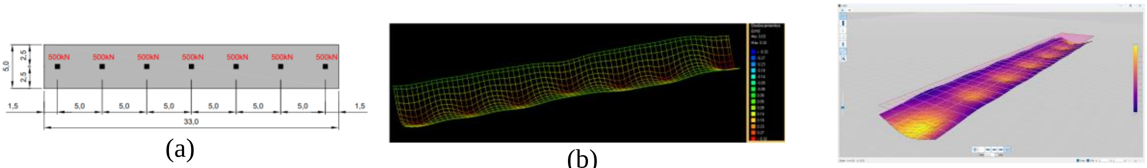
Table 1. Comparison of Results between CALCO (Cass [15]) and LAGI Radier.

Software	M_{max}(kNm/m)	Dif.(%)	v_{mas}(cm)	Dif.(%)
CALCO	78.178	2.03	0.530	2.83
LAGI	76.588		0.515	

6.2 Application 02

The second case is based on an example by Souza [14] and also analyzed by Braga [16]. It involves a concrete slab with a compressive strength f_{ck} of 30 MPa, measuring 33 m x 5 m and with a thickness of 0.3 m, discretized using a mesh of 0.5 m x 0.5 m. The slab is subjected to seven point loads of 500 kN each, arranged as described in Fig. 3(a). Additionally, a vertical reaction coefficient of 15,000 kN/m² was used.

Results related to the deformed surface and values for displacement and maximum moment for this case are shown in Fig. 3(b) and (c), and in Tab. 2.



(a)

(b)

(c)

Figure 3. Representations: (a) Application characterization; (b) Maximum displacement – CALCO; (c) Maximum displacement – LAGI Radier.

Table 2. Comparison of Results between Braga [16] and LAGI Radier.

Referência	M_{max}(kNm/m)	Dif.(%)	M_{min}(kNm/m)	Dif.(%)	v_{mas}(cm)	Dif.(%)
BRAGA	120.5	0.5	- 30.9	5.8	0.320	0.3
LAGI	119.9		- 32.7		0.319	

7 Conclusions

In light of the above, it is concluded that, despite technological advances that facilitate the work of structural engineers, technology cannot replace the need for detailed analysis and integrated, specialized knowledge. Thus, the analysis of soil-structure interaction is crucial at this moment. Therefore, the development of software like LAGI Radier becomes increasingly necessary for better analysis of soil-structure interaction behavior using the Grid Analogy technique. The formulation used in this work proved effective in processing the cases, with both numerical and graphical responses being quite satisfactory. The LAGI Radier software demonstrated considerable utility, offering a user-friendly structural modeling, rapid processing, and important graphical responses for understanding the behavior of raft foundations. This work highlighted the importance of validating proposed solutions and performing a detailed analysis of the results obtained. Additional studies are recommended, especially comparative ones involving different methods, such as the influence of prestressing forces on foundations.

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