Model for considering soil-structure interaction and its implementation in the optimal design of RC frame structures

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ABSTRACT

This paper proposes a methodology to simulate the soil-structure interaction (SSI) in structural optimization processes. The aim is to create a scenario more aligned with reality, which is not reflected in the traditional methods of considering perfectly rigid or articulated supports. A Winkler-type model is proposed where a hyperbolic equation that relates the pressure p with the settlement S is used to calculate the stiffness coefficient k. This coefficient simulates the interaction that causes additional deformation of the superstructure during the loading process, increasing internal forces. Several reinforced concrete frame structures with traditional rigid supports and the proposed SSI model are optimized to demonstrate the influence of this phenomenon. The results show that using traditional supports, as is commonly done, leads to inefficient superstructure design. Therefore, the proposed methodology is conducive to creating more realistic models that allow for more efficient and durable sustainable designs.

Keywords: soil-structure interaction; reinforced concrete; frame structure; optimization; Winkler model.

1. INTRODUCTION

One of the most debated aspects today by structural engineers is the need to minimize construction costs, material consumption, and the environmental footprint of the construction industry. This can be achieved through a more efficient use of building materials due to design optimization [1].

Reinforced concrete (RC) frame building structures are essential to the construction sector, so their environmental impact is quite significant. Although many studies have been carried out on how to improve the sustainability indexes of this type of structure, there are still some drawbacks. The first is the limited consideration of case studies. Most of them are simple elements or plane structures. Few authors have optimized the design of 3D RC frame structures with a realistic approach [2]. Besides, the few studies performed on more complex systems have the weakness of the supports considered. Authors usually assume structures with idealized supports (e.g., fixed), even when the soil and foundation assembly is not perfectly rigid. Support displacements (settlements) exist and influence the superstructure behavior, which is not the case with classical supports. This idealization leads to an inefficient design of the superstructure. Therefore, it will suffer accelerated deterioration with the

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consequent need for additional maintenance during its life cycle. It makes the design optimization lose all its validity [3].

This study proposes a model to consider the soil-structure interaction (SSI), mainly focused on its use in structural optimization of 3D RC frame building structures. The optimization objective is to minimize CO_2 emissions. The SSI model has a Winkler-type approach, in which a hyperbolic equation that relates the pressure *p* to the settlement *S* is used to calculate the stiffness coefficient *k*. The use of this type of equation to model soil stiffness has been validated by several authors on different types of soils [4]. Therefore, the results aim to compare optimized designs of structures (1) with classical supports and (2) considering the SSI using the proposed model.

2. METHODOLOGY

Fig. 1a shows the three case studies used. In case 2, the length of the spans is increased to 8 and 6 m (direction of the "x" and "y" axis, respectively), and case 3 is similar in plan to case 1, but with an additional level.

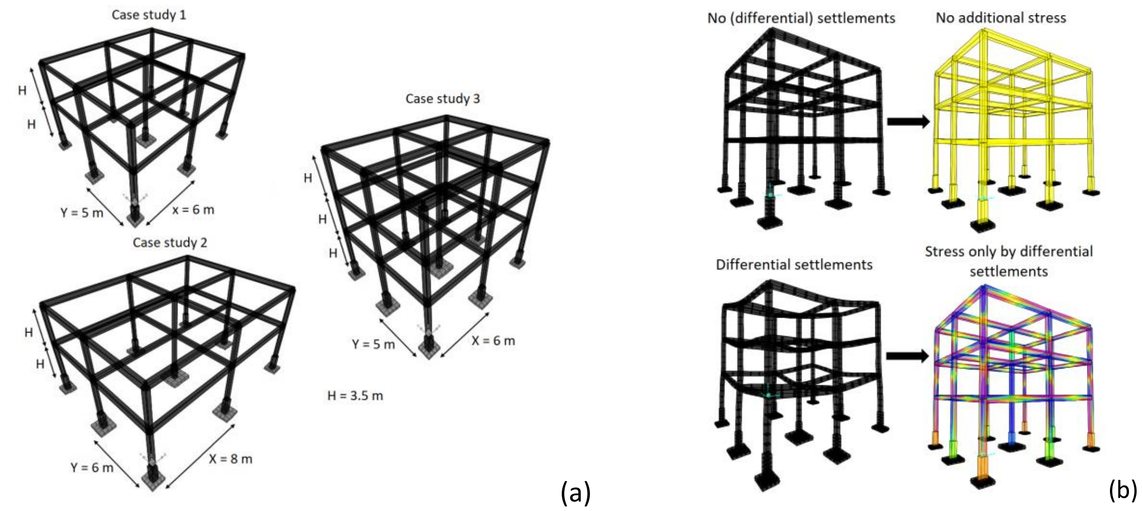

Figure 1. *Some aspects of the methodology: (a) three case studies, and (b) representation of the additional stress produced by differential settlements.*

When considering soil-structure interaction, the soil beneath the foundations is considered to deform during the loading-unloading process. Presumably, these settlements are not equal in all supports since, even if the soil is the same (as in this study), the forces reaching each group of foundations are different. These differential settlements, even in the permissible range, cause the superstructure to deform and additional stresses to appear (see Fig. 1b). This phenomenon does not occur in models with rigid supports.

$$k = \tan\alpha = \frac{p}{S} = \frac{q^{*}_{br\_II} - p}{\bar{S}\cdot\left[\left(\frac{q^{*}_{br\_II}}{R'^{*}}\right) - 1\right]} \qquad (1)$$

Eq. 1, proposed by [5], is used to obtain the soil stiffness coefficient *k*. Here, *p* and *S* are the foundation's acting pressure and settlement respectively. $\bar{S}$ is the base settlement for an acting pressure equal to the soil base linearity limit stress R'^{*}, and $q^{*}_{br\_II}$ is the base bearing capacity pressure based on expressions from the theory of plasticity. This coefficient *k* is applied to the nodes formed by discretizing the foundation base.

Another point highlighted in the study is how different soil types behave and how it is reflected in the proposed model. For this purpose, two different soil types are considered, one predominantly cohesive (FI = 8º, C = 60 kPa, E = 12 MPa, $\gamma = 19$ kN/m³, $\mu = 0.40$) and one predominantly frictional (FI = 32º, C = 10 kPa, E = 15 MPa, $\gamma = 17.5$ kN/m³, $\mu = 0.30$). The hypothesis is that, although cohesive soils are more deformable than frictional, differential settlements are more significant in the latter. It is because the behavior is generally nonlinear in this type of soil, while in the former, it is usually linear [1].

The algorithm considering the SSI in the optimization process starts with a model with classical supports. After performing the analysis of this model, a pre-design of the foundations is made, and the stiffness coefficient *k* is calculated for each foundation. Both the foundations and the springs of stiffness *k* are included in the initial model. Lastly, the ultimate design is made with the internal forces of this model with SSI, and the final outputs of the structure are calculated (CO_2 emissions in this case).

The optimization problem is formulated with 16 discrete variables that regulate the dimensions of the cross sections of the frame elements, the foundations base's rectangularity, and the concrete's quality in the three groups of structural elements (beams, columns, and foundations). The objective is to minimize the CO_2 emissions produced both by the manufacture of building materials and by construction activities on site. The constraints ensure that the designs meet the requirements of the structural codes. The Biogeography-Based Optimization (BBO) [6] heuristic is used as the optimization algorithm. For more information on the methodology in general, refer to [1 ,2, 3].

3. RESULTS AND DISCUSSION

The fundamental hypothesis of the study is that the superstructure of models that consider SSI is more stressed than models with classical supports. A direct way to verify this approach is by optimizing the design of each model and comparing the outputs. Fig. 2 shows that optimized designs of models with SSI lead to more emissions than traditional models (no SSI). It does not mean that not considering the interaction is more beneficial, but quite the opposite. Structures with rigid supports require less material in the superstructure since they are less stressed. However, the supports are not rigid, and differential settlements exist in practice. Therefore, by optimizing the design of a structure with idealized supports, a considerable percentage less construction material is used than is actually needed (see differences in percentages in Fig. 2 at the top of the bar charts).

The columns are the elements that change the most from one model to another (red arrows in Fig. 2). It is because the increase in bending resulting from differential settlements affects columns more than beams since the latter are more prepared to resist bending stresses. On the contrary, columns work mainly under axial load, so the increase in bending affects their design more. Another point is that frictional soils are more prone to differential settlements. The graph also shows the differences between the models with SSI and those with classic supports (*). The most significant differences are for case study 3. It obeys that the axial load reaching the foundations is higher by having an additional level. Therefore, the phenomenon of differential settlement becomes more acute.

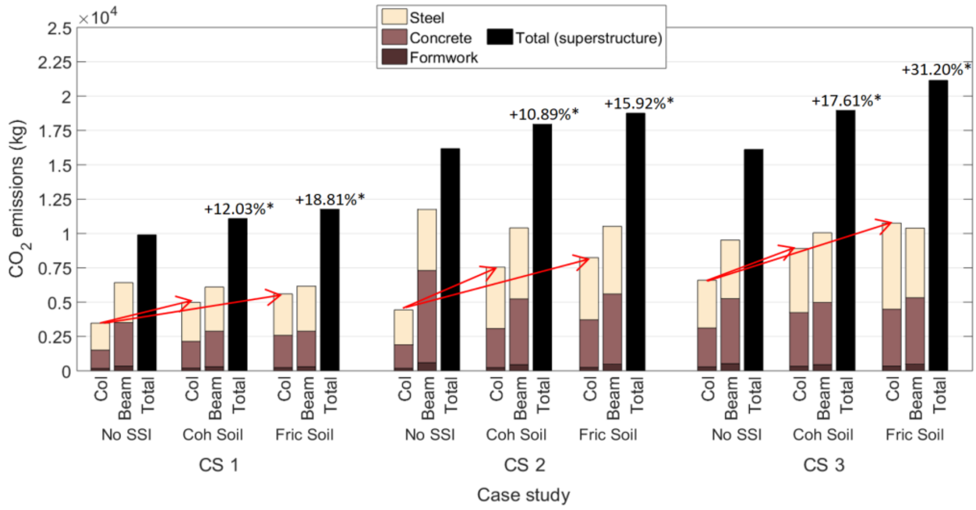

Figure 2. *Emissions for each optimal solution broken down by columns, beams and total of the superstructure. * Compared to models with idealized supports (No SSI)*

4. CONCLUSIONS

This study proposes a model for considering soil-structure interaction in optimizing reinforced concrete frame buildings. The results indicate that the common practice of assigning idealized supports provides inefficient designs. Therefore, the proposed methodology is highly beneficial for obtaining durable and sustainable structures.

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