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Influence of soil-structure interaction modeling on the behavior of multi-story plane steel frames with shallow footing foundations

Influência da modelagem da interação solo-estrutura no comportamento de pórticos planos de aço de múltiplos andares com fundação rasa

Influencia del modelo de interacción suelo-estructura en el comportamiento de pórticos planos de acero de varios pisos con cimentaciones de zapatas superficiales

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Abstract
Traditionally, structural analysis is based on the hypothesis that supports are indeslocable due to simplicity. However, the conventional design in which settlements of foundation elements are disregarded can lead to physical results that are incompatible with reality. This work aims to analyze the influence of the consideration of soil-structure interaction (SSI) on the responses of steel structural elements obtained by a static second order analysis. Furthermore, it is evaluated the responses obtained by different types of procedures for the consideration of soil stiffness in the structural analysis. Solid elements considering linearly elastic material parameters and spring elements based on the Winkler theory are employed. The analyses were performed with the commercial software SAP2000. Plane steel frames models were analyzed, either considering conventional supports or taking into account the soil-structure interaction. Shallow footing foundations are considered. Three frames with the same characteristics, but with a different number of floors were analyzed, showing the influence of the height increase and the building stiffness on the SSI results. It has been shown that the consideration of the effects of soil-structure interaction on structural analysis of buildings can have a significant influence on the stress distribution, displacements and structural behavior. In addition, it is concluded that the structural capacity of steel frames can be affected by the type of support adopted and by changes on the way the model considers soil deformation.
Keywords: Second order analysis; Soil-Structure Interaction (SSI); Spring elements; Continuous medium.

Resumo

Tradicionalmente, a análise estrutural é baseada na hipótese de que os suportes são indeslocáveis devido à simplicidade. Entretanto, o dimensionamento convencional em que os recalques dos elementos de fundação são desconsiderados pode levar a resultados físicos incompatíveis com a realidade. Este trabalho tem como objetivo analisar a influência da consideração da interação solo-estrutura (ISE) nas respostas de elementos estruturais de aço obtidas por uma análise estática de segunda ordem. Além disso, avaliam-se as respostas obtidas por diferentes tipos de procedimentos para a consideração da rigidez do solo na análise estrutural. Elementos sólidos considerando parâmetros de material linearmente elástico e elementos de mola, baseados na teoria de Winkler, são empregados. Modelos de pórticos planos de aço com fundações rasas foram analisados por meio do software comercial SAP2000, considerando apoios teóricos ou a interação solo-estrutura. Foram analisados três pórticos com as mesmas características, mas com número de pavimentos diferentes, afim de avaliar a influência do aumento da altura e da rigidez da edificação nos resultados. Foi demonstrado que a consideração dos efeitos da interação solo-estrutura na análise estrutural de edifícios pode produzir uma influência significativa na distribuição de tensões, deslocamentos e comportamento estrutural. Além disso, conclui-se que a capacidade estrutural de pórticos de aço pode ser afetada pelo tipo de apoio adotado e por mudanças na forma como o modelo considera a deformação do solo.
Palavras-chave: Análise de segunda ordem; Interação solo-estrutura (ISE); Elementos de mola; Meio contínuo.

Resumen

Tradicionalmente, el análisis estructural se basa en la hipótesis de que los soportes son indesplazables por su simplicidad. Sin embargo, el diseño convencional en el que se desprecian los asentamientos de los elementos de cimentación puede dar lugar a resultados físicos incompatibles con la realidad. Este trabajo tiene como objetivo analizar la influencia de la consideración de la interacción suelo-estructura (ISE) en las respuestas de los elementos estructurales de acero, obtenidas mediante un análisis estático de segundo orden. Además, se evalúan las respuestas obtenidas por diferentes tipos de procedimientos para la consideración de la rigidez del suelo en el análisis estructural. Se emplean elementos sólidos considerando parámetros de materiales linealmente elásticos y elementos resorte basados en la teoría de Winkler. Se analizaron modelos de pórticos planos de acero con cimentaciones superficiales utilizando el software comercial SAP2000, ya sea considerando soportes convencionales o teniendo en cuenta la interacción suelo-estructura. Se consideran cimientos de zapatas poco profundas. Se analizaron tres pórticos con las mismas características, pero con diferente número de pisos, mostrando la influencia del aumento de altura y la rigidez del edificio en los resultados. Se ha demostrado que la consideración de los efectos de la interacción suelo-estructura en el análisis estructural de edificios puede tener una influencia significativa en la distribución de tensiones, desplazamientos y comportamiento estructural. Además, se concluye que la capacidad estructural de los pórticos de acero puede verse afectada por el tipo de soporte adoptado y por cambios en la forma en que el modelo considera la deformación del suelo.
Palabras clave: Análisis de segundo orden; Interacción Suelo-Estructura (ISE); Elementos de resorte; Medio continuo.

1. Introduction

The soil-structure interaction (SSI) has been a concern in several studies since the placement of idealized support conditions during structural analysis can lead to results that are quite distant from the physical reality (Ritter et al., 2020). As a result, there is still a lack of provisions in building design codes that guide the consideration of soil-structure interaction in structural designs and that, at the same time, can be easily applied in design offices.

The development of computer programs made it possible to model soil-structure interaction problems, and consequently, to obtain more accurate results about the stability of a structural system. Several soil-structure interactions methods for numerical modeling, indicating their benefits and limitations, as well as the computer programs available for such analysis are proposed in the literature, to quote Ritter *et al*. (2020), Pavan *et al*. (2014), Marques *et al.* (2021), Ada and Ayvaz (2019), Chore and Ingle (2001, 2008), Chore *et al.* (2009), Saha *et al.* (2020), Dutta and Roy (2002), Garg and Hora (2012), Yesane et al., (2016) and Darbandsari and Kashani (2018).

For SSI consideration, simplified methods can be employed, such as the discretization of the soil through reaction coefficients, or advanced methods, such as the Finite Element Method (FEM) and the Boundary Element Method (BEM). The spring discretization method has the advantage of simplicity and speed of application. It eliminates the use of large computational resources or the need of knowledge of many soil parameters; however, it has the disadvantage of not considering soil continuity. Based on the Winklerian springs, Guimarães et al., (2018, 2020) developed a comparative study considering steel frames on shallow footing foundations and pipe foundations in order to analyze the effects of soil-structure interaction. Fuchs and Assis (2017) carried out the analysis of a plane frame under idealized support conditions, Winkler spring supports, which do not consider the influence that one foundation causes on the other, and, finally, an analysis based on a "continuous springs" model, that is, a mesh of springs that takes this influence into account. Regarding the internal forces in the structure, great differences were observed between the model with idealized supports and the two models of springs, with no great differences between the latter two. The spring's models presented greater displacements than the model with idealized supports. In addition, between the springs' models, the one with continuous springs presented the greatest absolute vertical settlements.

After the introduction of the Finite Element Method, the idea of modeling the soil as continuum was developed. In this context, one can mention the work of Shoaei *et at.* (2015), Venanzi e tal., (2014), Farouk and Farouk (2016), Nikolaou, Georgiadis and Bisbos (2016), Swamy *et al.* (2011) and Mitropolol *et al.* (2016).

The choice of using advanced methods depends on the problem to be analyzed, in general the BEM is more effective in problems in which the study domain is infinite or semi-infinite, which is the case of soil simulation. The FEM is more used for superstructure analysis. The coupling between the methods is widely used in the study of soil-structure interaction, as seen in research conducted by Almeida and Paiva (2011; 2004) and others.

Major part of the research in this field is focusing on the analysis of the maximum lateral displacement, the inter-story drift and the internal forces without including the second-order effects. Usually, displacements and strains are assumed to be small in the structural analysis. This means that the geometrical characteristics of the structure do not vary during loading, known as the first-order effect (Silva *et al*., 2018; Viana *et al*., 2020). However, large displacements and strains can occur when buildings are under large wind loadings and due to the effect of unfavorable soil–structure interactions. In this case, the inter-story drift maybe large and originate additional forces and moments in the structure (Saha *et al*., 2020; Silva *et al*., 2018), produced by the second-order effects.

Some studies have revealed the existence of several models of SSI, and the most adopted by the authors has been the Winkler spring model. It is observed that most of the works are dedicated to the analysis of concrete structures. Therefore, the objective of this work is to investigate the influence of different types of soil-structure interaction modeling on the second-order behavior of multi-story plane steel frames with shallow footing foundations subjected to static loads. P-delta second-order effect depict the phenomenon whereby an additional moment is developed in a column due to the combination of axial load and lateral sway. It can result in lateral deflections higher than those resulted from lateral loading alone, called second-order deflections. The soil stiffness is included by springs and by modeling a continuous medium with finite elements. The spring model adopted is based on Winkler theory. In addition, this work considers a model of springs mesh in which the spring parameters are assigned according to the soil properties.

2. Bibliographic Review

The complexity of soil behavior has brought the development of several models of soil based on theory of elasticity, plasticity and visco-elasticity for the analysis of soil-structure interaction problems. The simplest type of idealized soil response is obtained by assuming the supporting soil as a linear elastic continuum. Nevertheless, the simplified soil modeling, without considering its nonlinear behavior, can result in permanent damage to the building, thus compromising its useful life and possibly leading to its collapse. Therefore, a detailed analysis of the geotechnical profile by the designer is essential in such a way that the hypotheses considered are in favor of safety.

Two basic classical approaches have been used and reported in literature to represent the soil-structure interaction problem. In the following sections, the Winkler model, the spring mesh model and the continuum model are briefly described.

2.1 Winkler model

According to this idealization, soil is modeled as a series of closely spaced, mutually independent, linear elastic vertical springs, which, evidently, provide resistance in direct proportion to the settlement (D_z) of the foundation. In the Winkler model, the properties of the soil are described by one parameter (K_v), which represents the stiffness of the vertical spring. Due to its simple mathematic formulation, the model can be easily employed in several problems and gives satisfactory results in many practical situations. However, it is considered as an unrefined approximation of the true mechanical behavior of the soil, since it is unable to take into account the continuity and cohesion of the material. The assumption that there is no interaction between adjacent springs, also results in overlooking the influence of the soil on sides of the foundation.

Equation (1) represents this proportionality, where N is normal load, K_v is the proportionality constant, also known as the subsoil reaction coefficient, or simply as the spring coefficient, and D_z is the settlement.

$$N = K_v.D_z \tag{1}$$

The spring parameter value (K_v) of the soil can be determined by means of correlations, in which K_v value is estimated from soil parameters, such as the modulus of elasticity, the Poisson's ratio, or the allowable stress of the ground. The correlation can be made using empirical formulas in the literature, or by manipulating equations that predict the settlement of a given foundation.

Assuming an area (A) and a constant axial force along the length of the spring, the spring elastic constant in the axial direction is given by Equation (2), with (L) being the original distance between the points and (E) being the elasticity modulus of soil.

$$K_v = EA/L \tag{2}$$

The Winkler's model considers a simplified soil modeling. For a more realistic representation of the soil, it is necessary to model the soil mass as a spring mesh or as a continuous medium.

2.2 Elastic spring mesh model

In order to improve the response provided by the Winkler model, researchers have proposed models considering the connectivity and interaction among the springs, as the model proposed by Kurian and Manojkumar (2001). In this model, the interconnection of the springs is ensured by connecting the ends of the vertical springs to horizontal springs, forming a mesh of continuous springs. This model has the advantage of taking into account the effect of the soil beyond the area carried by the foundation.

The spring mesh is a system of vertices and edges, in which each edge is a linear spring. The linear springs are connected at the vertices. This system is intuitive and simple to implement. However, they are not necessarily exact because they are not built on continuous elasticity. The determining spring stiffness parameters for simulation of soil with high accuracy still remains a challenge.

2.3 Elastic continuum model

One of the solutions for considering the soil as a continuous medium is the use of numerical methods such as the FEM, which determines approximate solutions by subdividing the domain of a problem into smaller parts.

Soil mass consists of discrete particles compacted by intergranular forces. The problem involves boundary distances

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and loaded areas which are large when compared to the size of individual soil grains. Thus, the body of composed discrete molecules get transformed into a statistical macroscopic equivalent, possible to be treated mathematically.

In elastic continuum model, the behavior of soil is idealized as three-dimensional continuous elastic solid. The distribution of displacements and stresses in media remain continuous under the action of external force system. A continuous function is assumed to represent the behavior of soil medium. In this idealization, soil is assumed to be semi-infinite and isotropic for the sake of simplicity, even though the effect of soil layering and anisotropic behavior may be accounted for in the analysis. This approach provides more information about stress and strain in the soil mass than the Winkler model.

3. Materials and Methods

3.1 Structural models

Several authors have shown that the difference between the results for 2D and 3D models is negligible when considering the rigid soil (Dutta & Roy, 2002). In this research, four types of structural models for plane steel frames with three different heights are analyzed considering theoretical supports (TS) with fixed supports and the others considering SSI based on Winkler's theory (W), the continuous spring mesh (SM) and the soil modeling as a continuous medium (CM).

Three frames with two spans are analyzed, with 4, 7 and 11 floors, as shown in Figure 1, which indicates the concentrated vertical loading on the columns, distributed vertical loading on the beams and horizontal loading due to the action of the wind. The external and internal columns profiles adopted from 1st to 4th floor are, respectively, PS 500 x 300 x 16 x 8 and PS 500 x 300 x 19 x 9.5, from 5th to 7th floor are PS 500 x 300 x 12.5 x 8 profiles, from 8th to 11th floor are PS 500 x 300 x 9.5 x 6.5 profiles, and all beams are composed of W 530 x 66 profiles. Figure 2 shows the numbering of the nodes and elements used for non-braced frames up to 11 floors and indicates the lengths of the spans of the beams and the heights of the floors.

The steel frames were investigated considering the elastic analysis in second order theory by means of the P-delta method (Chen, 2018), in the SAP 2000 software, aiming to evaluate the influence of the soil settlements on internal forces and lateral displacements. For the modeling of beams and columns of plane steel frames, frame elements are used in all models. For footing foundation modeling, plate elements with 4 nodes are used for rectangular elements and 3 nodes for triangular elements in all SSI models. Solid elements are used for modeling the soil in the continuous medium model. This type of element has the prismatic shape of a hexagon defined by eight nodes and six faces.

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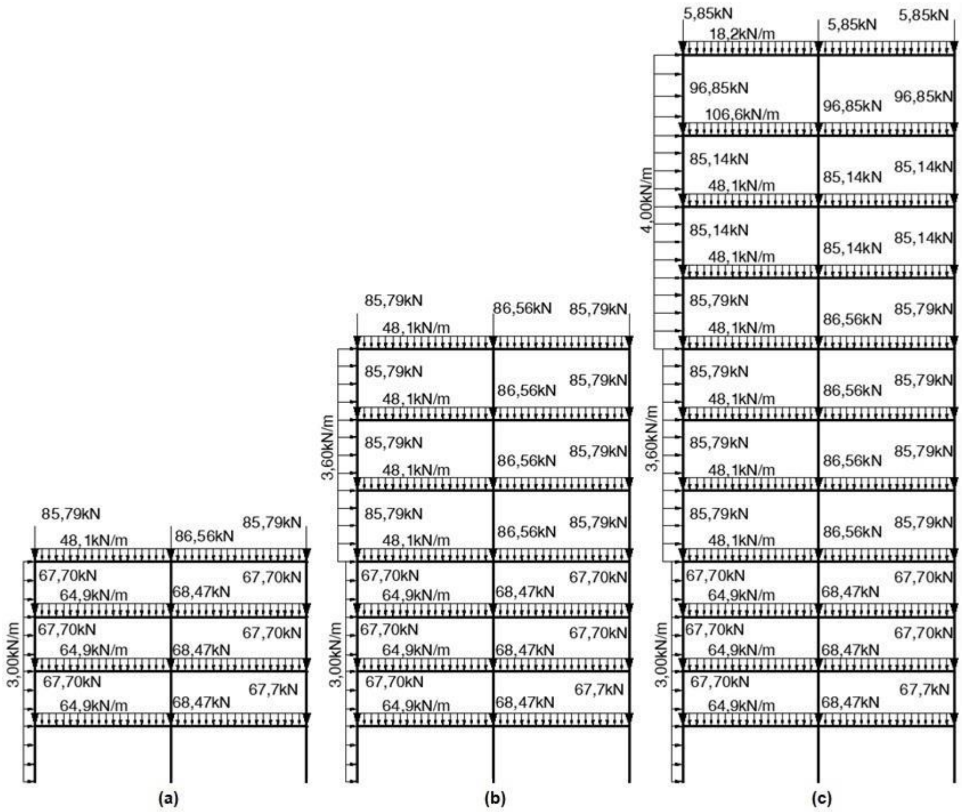
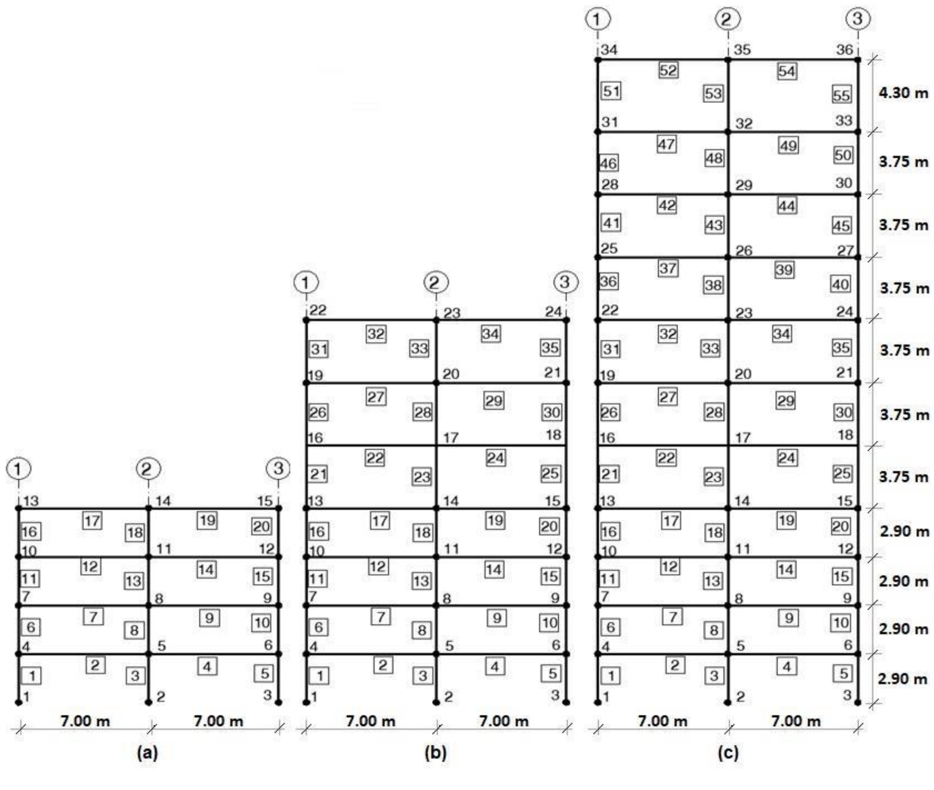
Figure 1 – Plane steel frames with three different heights (a) 4-story (b) 7-story (c) 11-story.



Source: Authors.

Figure 2 – Nodes and elements numbers for the steel frames with three different heights: (a) 4-story (b) 7-story (c) 11-story.



Source: Authors.

3.2 Soil Parameters

For modeling the soil as an elastic medium, whether using springs or elements that simulate a continuous elastic medium, E and ν parameters are defined. The elasticity modulus of soil (E) can be related to the result of standard penetration test (N_{SPT}) through empirical correlations. A way to estimate this parameter is presented by Teixeira and Godoy (1996) given by equation (3), where the N_{SPT} (MPa) is the result of the standard penetration test, obtained in soil test reports, K e α are coefficients that vary depending on the soil type:

$$E = \alpha.K.N_{\text{SPT}} \tag{3}$$

The Poisson's ratio (ν) is defined by the relationship between the transverse strain and the longitudinal strain. For each type of soil, this parameter has typical values. The Shear Modulus (G) is defined as the ratio between the shear stress acting on a material and its angular deformation, and, for isotropic materials, it can be related to the elasticity modulus and to the Poisson's ratio.

For a more accurate analysis of the stress distribution in the soil due to the loads acting on the foundation elements, several field tests are necessary (Teixeira & Godoy, 1996), but, in the absence of these tests, it is suggested to use the stress bulb distribution that was proposed by Bowles (1988). Based on the stress bulb, it can be said that the foundation elements deform the soil to an average depth of twice the smallest width of the foundation (B). Below this depth, the influence of foundation loads on the soil tends to zero.

The soil is a clay-silt with increasing resistance along the depth. Table 1 shows the values of the elasticity modulus and the allowable stress on the soil. The elasticity modulus is obtained by equation (3), which relates the N_{SPT} and the coefficients α and K, respectively, equal to 5 and 0.25 MPa, for the type of soil adopted. The allowable stress on the soil, σ_{adm}, is determined by the number of penetrations divided by 5, in kgf/cm^2, as recommended by Moraes (1976) and the Poisson's ratio is considered equal to 0.3.

For the footing foundations, concrete with f_{ck} equal to 30MPa was considered. To define the dimensions, the highest frame was modeled with idealized supports, and the stability of the footing foundations was checked. Two sizes were defined: external footing foundation of 4x4x1.25m and internal footing foundation of 6x6x1.9m.

Table 1 – Soil parameters.

Depth (m)	N_{spt}	E (MPa)	σ_{adm} (MPa)
1	12	15.0	0.24
2	13	16.3	0.26
3	11	13.8	0.22
4	13	16.3	0.26
5	10	12.5	0.20
6	14	17.5	0.28
7	17	21.3	0.34
8	21	26.3	0.42
9	23	28.8	0.46
10	26	32.5	0.52
11	26	32.5	0.52
12	29	36.3	0.58
13	38	47.5	0.76
14	43	53.8	0.86

Source: Authors.

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3.3 Parameters for Winkler model (W)

To determine the stiffness of the springs, a weighted average of the values of K_v and K_h of the soil was taken, considering for this weighting the area of influence of the stress bulb, transmitted to the soil by the footing foundations. The coefficient of horizontal reaction of the soil K_h, presented by Barkan (1962), applied to surface foundations is defined by:

$$K_h = K_\tau C/\sqrt{A} \tag{4}$$

K_τ is equal to 0.868, determined as a function of the Poisson's ratio and the ratio between the smallest and largest footing foundation dimensions (B/L); A is the floorplan area of the footing foundation and C is a factor defined by equation (5):

$$C = E/(1 - \nu^2) \tag{5}$$

where E is the elasticity modulus of the soil and ν , the Poisson's ratio of the soil.

For the definition of the vertical reaction coefficient, or Winkler's spring coefficient, equation (6) is used, proposed by Perloff (1975), which takes into account the smaller footing foundation width, the Iw factor that depends on the shape, footing foundation stiffness and E and ν values. The footing foundations are square and rigid, so the value of Iw is equal to 0.82.

$$K_v = C/B/I_w \tag{6}$$

The coefficients K_v and K_h are shown in Table 2, for the peripheral and central footing foundations.

Table 2 – K_h and K_v values for external and internal footing foundations.

Depth (m)	External footing foundation K_h (kn/m³)	External footing foundation K_v (kn/m³)	Internal footing foundation K_h (kn/m³)	Internal footing foundation K_v (kn/m³)
1	3577	5025	2385	3350
2	3875	5444	2583	3630
3	3279	4607	2186	3071
4	3875	5444	2583	3630
5	2981	4188	1987	2792
6	4173	5863	2782	3909
7	5067	7119	3378	4746
8	6260	8795	4173	5863
9	6856	9632	4571	6421
10	7750	10889	5167	7259
11	7750	10889	5167	7259
12	8644	12145	5763	8097
13	11327	15914	7551	10609
14	12817	18008	8545	12005
Weighted Average	3712	5215	2839	3989

Source: Authors.

The footing foundations were modeled with shell elements, considering the compressive strength of the concrete f_{ck} equal to 30MPa, and they were discretized with dimensions of 1.0 m. For the springs, the average values of K_v and K_h were considered.

3.4 Parameters for continuous medium modeling (CM)

The solids were discretized with sizes of 1.0 m in all directions. The values attributed to each layer of elements along the depth were the values of E and ν presented previously. The shell elements, discretized with dimensions of 1.0 m, were connected to the solid elements through the nodes.

In order to analyze the soil-structure interaction, using the finite element method, it is necessary to define the dimensions of the solid that will be modeled for the representation of the geotechnical mass. The dimensions adopted for the mass must be such that all the deformation effects due to the applied stresses are included within that element. Therefore, the modeling was done using an iterative process, in which the size of the solid mesh was increased until the stress bulb was contained within the limits of the modeling and, also, until the results of displacements and internal forces were maintained constant.

3.5 Parameters for Continuous Springs Mesh modeling (SM)

Regarding the spring mesh, spring elements with lengths of 1.0 m were used in all directions, so that the values of the spring constants of equation (2) were such that A and L were unitary, K = E in the axial direction of the springs with the E values for each soil layer defined according to Table 1. To calibrate the spring mesh model based on the continuous medium model, it was necessary to adjust the transverse deformation which occurs with the solids that represent the soil due to the Poisson's coefficient. Therefore, in this direction, the value adopted for the spring stiffness was K= νE/4, with the divider 4 being equivalent to 4 springs that deform laterally due to axial compression loading in the spring cube. To define the extension of the spring mesh, the same criterion for modeling the continuous medium was used, which considers the size defined for the footing foundations, the influence of the stress bulb and the stability of the deformation results and internal forces.

In spring mesh model, springs are introduced in vertical and horizontal directions, simultaneously. Horizontal springs can be justified to avoid the handicap raised in the Winkler model. The calibration of horizontal stiffness plays a primordial contribution in this research.

4. Results and Discussion

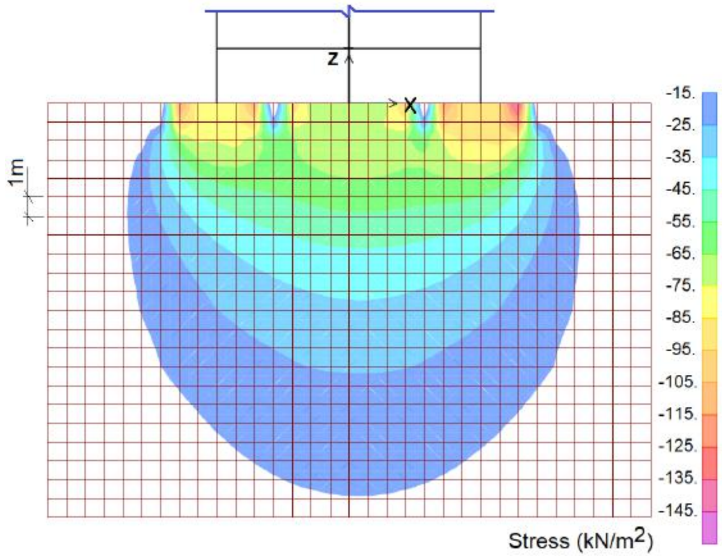
The distribution of stresses in the soil and the values of the nodes' displacements and the elements internal forces are presented in this section.

4.1 Stress bulb in the continuous medium model

In Figure 3, the diagram of stresses in the solid elements, which represent the supporting soil, for the 11-story steel frame is shown. The maximum stress in the contact of the foundation with the soil is q=145kN/m² and, close to the depth of 21m, the stress is q_0=15kN/m², showing a behavior very similar to the bulb proposed by Bowles (1988). Although the three footing foundations have a square section, the bulb of the three is added due to the proximity among them and the loading values, so that the soil does not manifest a stress bulb compatible with square footing foundations, whose q/q_0=0.1 ratio occurs close to the depth of 2B.

This type of modeling, which uses solid elements, is the only one among all the models analyzed in this work where it is possible to view the stress bulb. In the continuous spring mesh model, which comes closest in terms of refinement of the continuous medium modeling, there are no results of stresses, only deformations in the springs. In the Winkler model it is not possible to obtain information from the stress bulb.

Figure 3 – Stress bulb for the 11-story steel frame showing the pressure intensity q/q_0, based on the Boussinesq equation.

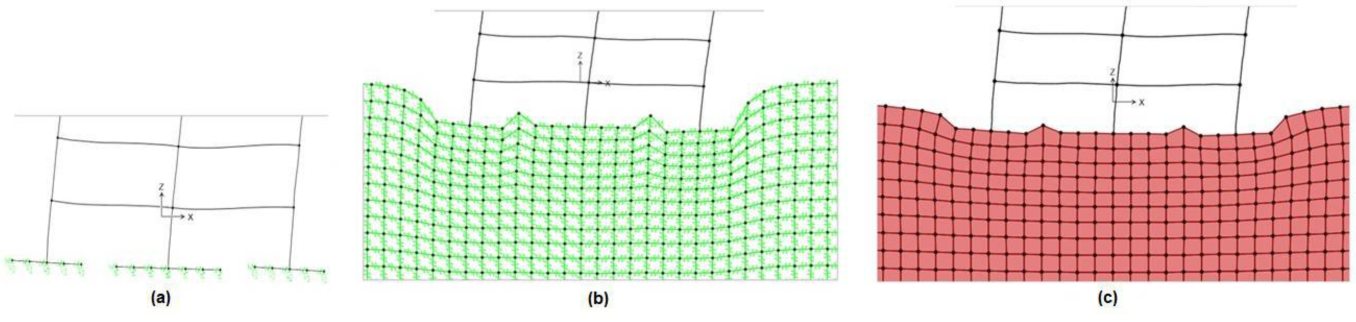


Source: Authors.

4.2 Displacement analysis

Figure 4 shows the displacements, with increased scale, considering the SSI behavior in the region where the foundation is supported. It is observed the similar behavior of the CM and SM models, as well as the difference of these models in relation to the Winkler (W) model. In the CM and SM models, the support footings are connected by soil elements. As a result, the deformation of a foundation element produces an influence on neighboring elements in such a way that the soil elements between the foundation footings have a different deformation in relation to the other nodes, which is the result of the "stuffing" caused by the pressure applied to the ground by each footing. In turn, adopting the W model, the footings deform independently.

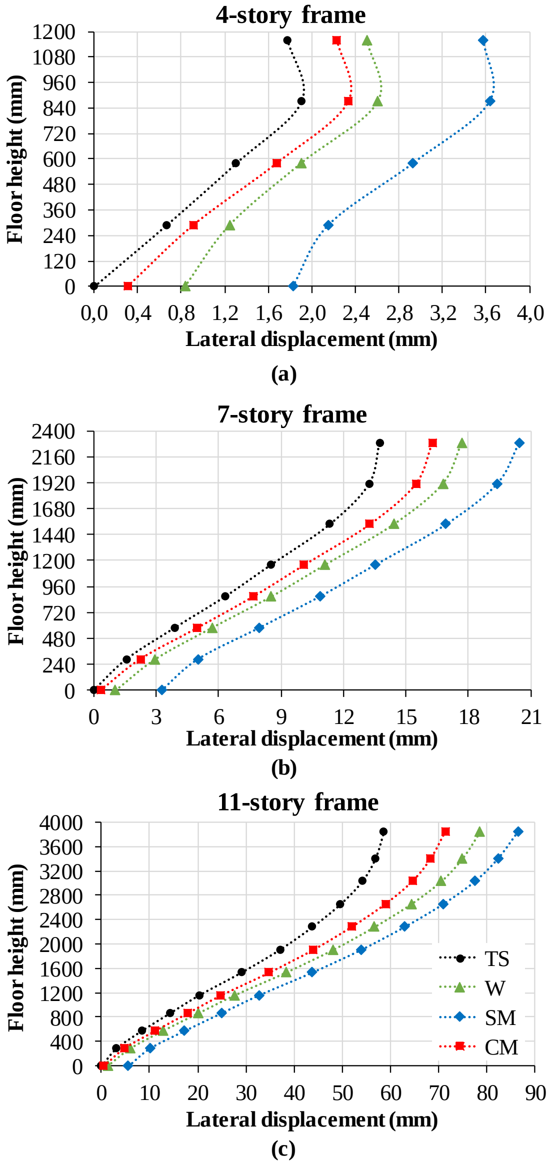
Figure 4 – Behavior of the models with SSI: (a) W model, (b) SM model, (c) CM model.



Source: Authors.

For the evaluation of lateral displacements and comparison of the models, the right column of the frames was chosen as a reference (axis 3 in Figure 3). Figures 5 and 6 show the lateral and vertical displacements at the top of the floors for steel frames with 4, 7 and 11 storeys for second elastic analysis and considering SSI. Abscissa axis refers to the displacement value in millimeters and the ordinate axis refers to the floor height value in millimeters. It is observed that the curves present a behavior of unbraced frames, as expected.

Figure 5 – Comparison of lateral displacements at the top of the floors for all models: (a) 4-story frame, (b) 7-story frame, (c) 11-story frame.



Source: Authors.

The effect of soil-structure interaction on top displacement of the frame is quite significant. Displacement is less for the analysis considering idealized supports, i.e., fixed base condition, and is greater when the effect of SSI is taken into consideration. Among the models that consider SSI, those with the use of springs (Winkler and continuous spring mesh) presented lateral and vertical displacements values higher than the values found in the model with continuous medium. The model that considers SSI by means of continuous spring mesh showed greater flexibility, with the highest values of lateral and vertical displacements, unlike the model that considers the continuous medium, which presented greater rigidity under the foundation. When the continuous spring mesh is considered in the analysis, lateral displacements are different from those obtained by the Winkler approach. The Winkler model disregards the effect of the continuity of the medium. This model considers that only in places of load application the soil undergoes displacement. It is observed that, in the case of the theoretical model with fixed supports, the lateral displacement value at the base is equal to zero and for SSI models are great than zero.

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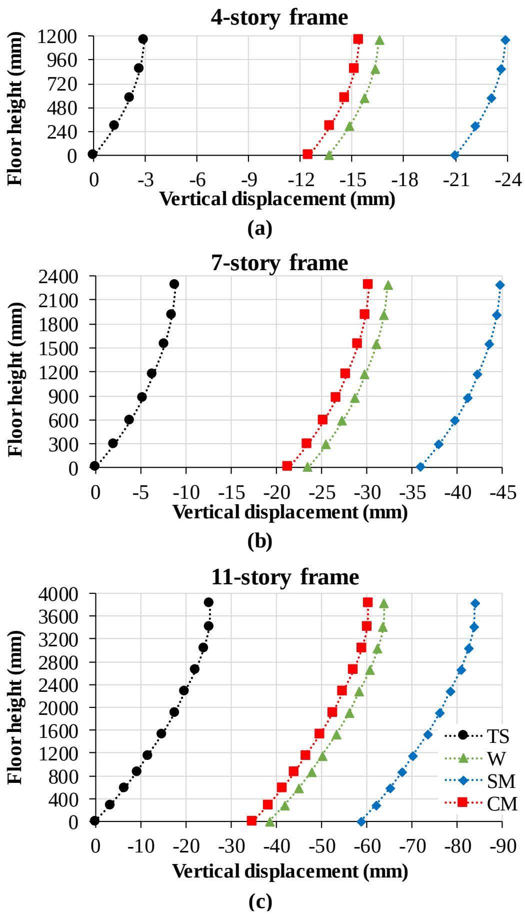
Figure 6 – Comparison of vertical displacements at the top of the floors for all models: (a) 4-story frame, (b) 7-story frame, (c) 11-story frame.



Source: Authors.

For the three steel frames, it was observed that the height of the building influences the behavior of the models for lateral displacements (Figure 5) and consequently the 2nd order effects because the distance between the lines of the graph did not remain constant with this increase. The soil behavior influences the global stability of the frames. When the SSI is considered, an increase in lateral displacement occurs in the structure, consequently, an increase in the P-Δ effect is observed in relation to the conventional analysis with idealized supports. For vertical displacements (Figure 6), the values became higher with the increase of the number of floors, but the distance between the lines of the graphs remained constant. Therefore, all models exhibited similar behaviors with respect to absolute vertical displacements.

Table 3 shows the results of the differential settlements for all models considering the SSI, for the frames with 4, 7 and 11 floors. In the assessment of differential settlements, which are of great importance considering the fact that they impose greater or lesser soliciting efforts on the structure, it is observed that the models of continuous spring mesh and continuous medium presented the highest values of settlement.

Table 3 – Differential settlements on the foundation for SSI models.

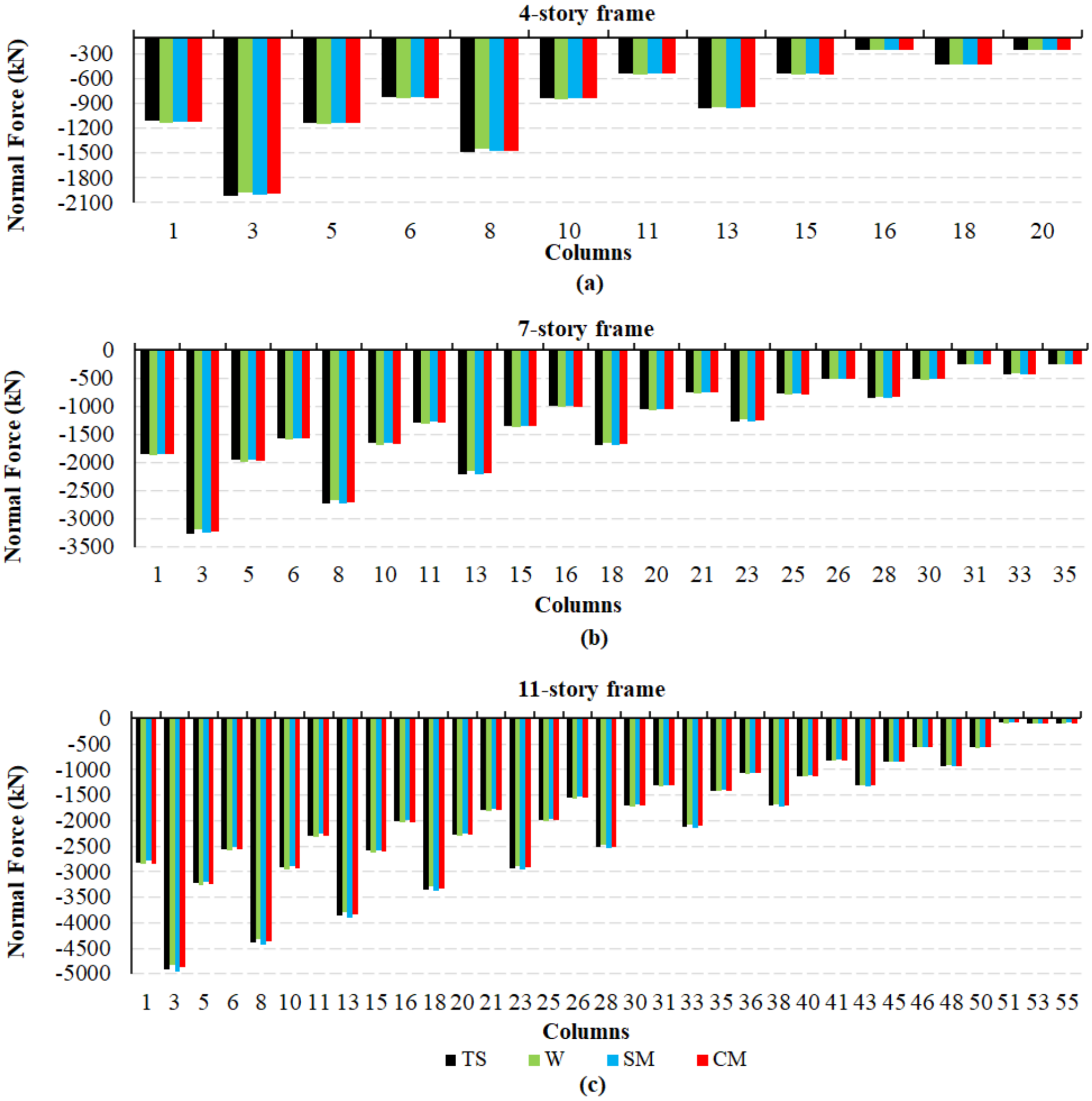
Node	Differential settlements (mm)								
	4-Story frame			7-Story frame			11-Story frame		
	W	SM	CM	W	SM	CM	W	SM	CM
Settlement 2-1	-0.6	-0.9	-1.2	-0.7	-1.0	-1.7	-1.1	-2.0	-2.6
Settlement 3-2	0.4	0.5	1.0	-0.7	-1.0	0.6	-3.9	-5.3	-1.3

Source: Authors.

4.3 Analysis of internal forces in frames

The graphs in Figure 7-a, b, c show the result of the normal force on the left, middle and right columns of the 4, 7 and 11-story frames, respectively, considering all the models. It is observed that the model type does not significantly alter the values of this internal force in structural members.

Figure 7 – Normal forces in the left, middle and right columns of 4, 7 and 11-story frames.



Source: Authors.

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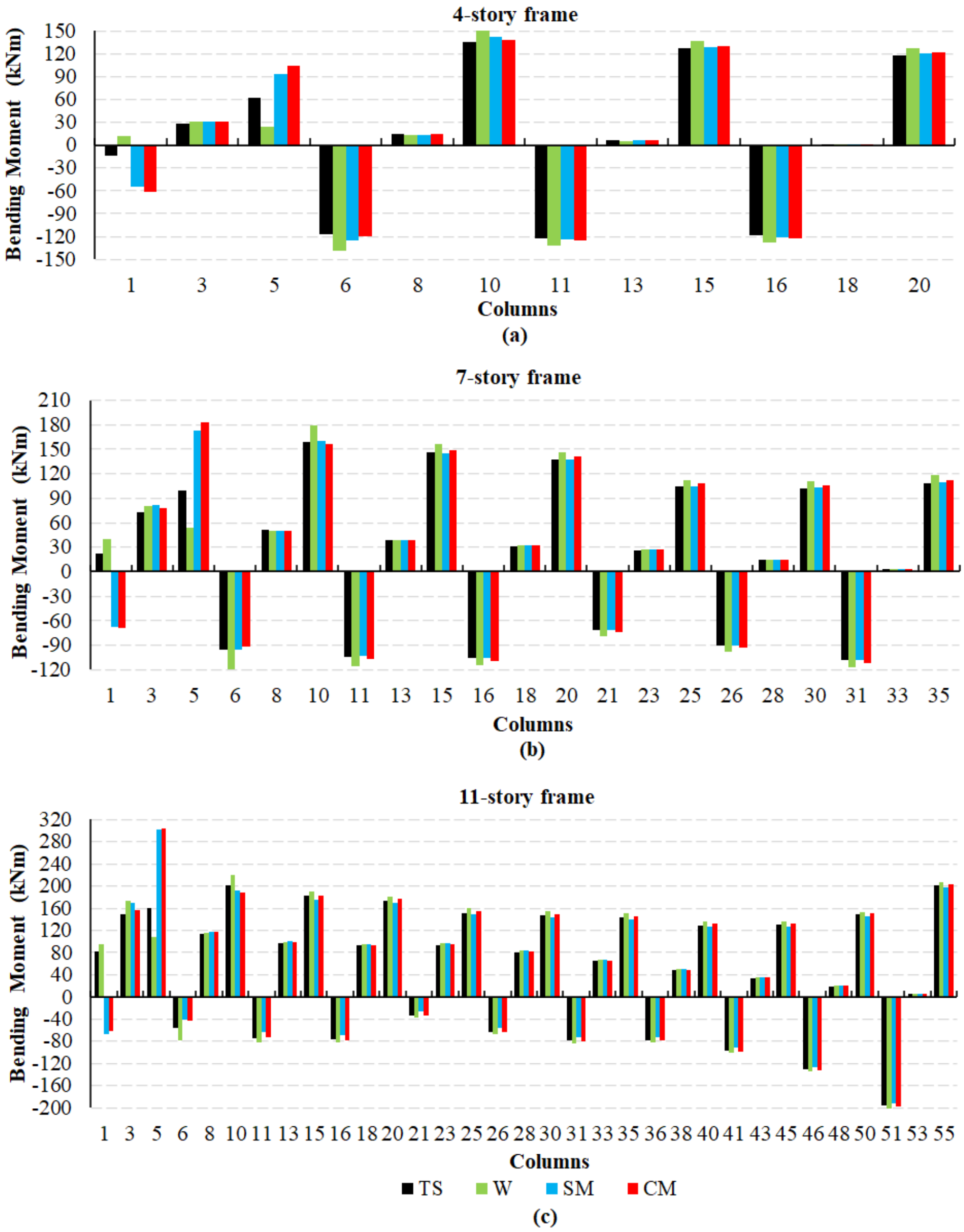
The graphs in Figure 8-a, b, c show the result of the bending moment at the lower end node of the left, middle and right columns from the 4, 7 and 11-story frames, respectively, considering all models. It is observed that the type of model influences the result of the first-floor columns in a very significant way. Differences in this soliciting effort can be observed among the models, including the inversion of signals for node 1 at the column base.

The bending moment in the columns of the first floor was the soliciting effort that presented the greatest variation and percentage difference when comparing the models with SSI to the models with theoretical supports, reaching a difference of 400% for the highest frame. It can be said that the difference in the values of this effort is the most important aspect to be evaluated, because the bending moment determines the structural design of the column.

Figure 8 – Bending moment at the lower end node of the left, middle and right columns from the 7-story frames of 4, 7 and 11-story frames.



Source: Authors.

It was observed that, for each type of modeling, even using the same parameters, that is, the same soil survey and the elasticity modulus (E) and the Poisson's ratio (ν), the results found for each model showed great variations among themselves, mainly at the base of the building.

It can also be observed, through the analysis of differential settlements, that considering the influence of the pressures of an isolated foundation on neighboring foundations may increase the differential settlements at the base, evidenced by the difference in the bending moment values in the elements of the first floor.

In addition, the results obtained in the analysis reveals a similarity regarding the internal forces between the model considering the spring mesh and the model considering the continuous medium.

5. Conclusion

The main objective of the study was to investigate the influence of the consideration of soil-structure interaction (SSI) on the responses of steel structural elements obtained by a second order analysis. To this end, the results obtained by several types of models including the effects of soil stiffness were compare with those provided by the use of idealized support conditions.

Three steel frames with different heights were analyzed, using for each one, three models to simulate the flexibility of the soil, in order to evaluate the behavior of the structure as its stiffness increases. Comparative analysis of the results obtained from the internal forces (normal force and bending moment) and the displacements among these models were presented.

The Winkler model considered the settlements by replacing the springs in the foundation. In addition to the settlement caused by the springs, the continuous spring mesh model considered the influence that one foundation causes on the other. The continuum medium model took into account the continuous behavior of soil, idealized as three dimensional continuous elastic solid. The greatest divergence of results considering all models was found in the displacement values. The spring models presented greater displacements, both in the vertical and horizontal directions, allowing the displacement of the building until the stabilization of the settlements. When comparing the values of the internal forces and differential settlements, the results of this model are similar to the results obtained considering the continuous medium model, but without maintaining a standard.

Among the SSI models studied in this work, the continuous medium model is the only one that provides information on stress distribution along the soil depth. This model, when compared to the others, is more suitable for evaluating responses related to the soil, which gives it greater credibility.

Regarding the comparison between the frames with different heights, it can be said that the structure’s stiffness significantly influences the structural elements closest to the foundation. The bending moment in columns located at the base of the buildings was the soliciting effort that presented the greatest variation and percentage difference when comparing the models with SSI to the models with theoretical supports.

Therefore, the SSI is essential for reasonably obtaining accurate predictions of both soil settlements, displacement in the nodes and internal forces in the structural members. Even if neglecting the interaction effect does not result in serious damage, it would however reduce the margin of safety, or result in overestimation or underestimation of the real bending moments of the structural members. Finally, it must be stressed that the conclusions of this study rely on the assumption that the soil is a linear elastic material. Thus, the results should be further checked against results obtained from analyses in which the soil is modeled as a nonlinear material.

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