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Correction coefficients of distortion and vibration period for buildings due to soil-structure interaction

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Abstract. The present research analyzed the influence of the soil structure interaction (SSI) in buildings, varying geotechnical parameters and height, considering 3 international codes. The responses obtained from the structures taking into account the SSI, were compared with the responses of fixed-base buildings, being the main control variables: the period and the drift. It was determined that the estimated range in which the period of the structure increases is from 30 to 98%, demonstrating the influence of considering soil flexibility. Due to the variability of the responses obtained, an adjustment factor is proposed to predict said amplification of the control variables, depending on the height of the building and the ground.

1. Introduction

The conventional analysis performed for the modeling of a building is based on recessing the structure considering an infinitely rigid floor. This idealization does not reflect the real behavior of the soil since it, depending on its geotechnical parameters, provides a certain stiffness that is related to an elasto-plastic behavior [1].

A study prepared by Karapetrou et al. [2] showed that the responses obtained considering the fixed base can lead to non-conservative results such as displacements and periods, which can be amplified in soft soils. Regarding the period, it was determined that the main effect generated by an SSI analysis is the lengthening of this,compared to the rigid base condition, being one of the main causes of this change, the ground in foundation [3]. Similarly, Aydemir et al. [4], evaluated the behavior of structures considering SSI under the effect of an earthquake. The authors verify the increase in the period and demonstrate that the influence of considering such interaction is greater in soft soils. In addition, Joy et al. [5], they proposed a methodology to perform the pushover analysis considering SSI. This study demonstrated the importance of considering the soil-structure interaction in the design of buildings, demonstrating how displacements increase. On the other hand, Valdebenito et al. [6], analyzed the effects of an earthquake of magnitude Mw = 8.2 and the damaged caused to the armed masonry structures. With the explorations carried out, it was demonstrated that the soil-structure interaction played a significant role in the buildings that suffered major damage. The predominant frequency of the soil was very similar to the frequency of buildings with greater structural damage, this correlates with the effects of resonance, an effect that in several of the cases analyzed could have increased seismic demand and thereby justify the increase in damage observed.

This research seeks to determine the impact of considering soil flexibility through an SSI analysis, in relation to two variables: period and drift. The period is one of the most important variables because it allows us to control possible resonances during a seismic event; on the other hand, displacements are closely related to the potential for structural failure. As a main result, it was determined that the percentage increase in the period, for a model that considers SSI, is in a range of 30 to 98% and with respect to drifts between 23 and 145%. Due to the variability in the amplification of the responses obtained, a correlation of data is proposed to establish a function that allows calculating said amplification depending on the floor and the height of the building.

2. Method

To make a correct prediction of the amplification behavior of the control variables, the answers will be calculated considering both idealizations of the soil behavior (SSI and fixed-base). With this, the percentage variation will be determined based on the height of the building, code used and geotechnical parameters for each structure. With the percentages obtained, it will be determined if the correlation of data is correct. For this, the proposed function will be validated by checking with a 95% reliability. This reliability will be applied to the own coefficients of the established regression.

The use of the equations, for the calculation of the amplification factors, is limited to a foundation system consisting of combined footings, for structures that vary between 4 floors (12 meters) to 12 floors (35 meters) and soil types employees in the study.

3. Analysis

In the first instance we will proceed with the analysis considering fixed-base. The buildings will be modeled and analyzed with the ETABS 2016 computational tool. The resulting drifts for both directions are shown in the graphs (figure 1 and figure 2), varying the soil parameters and the height of the building.

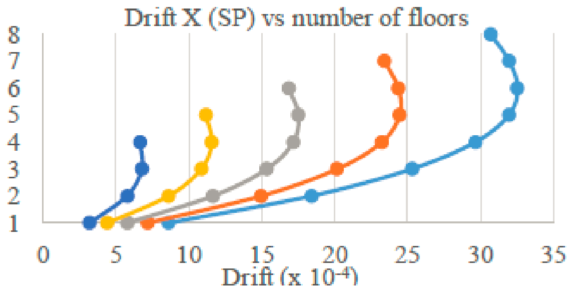

Figure 1. Drift X (SP) from 4 to 8 floors

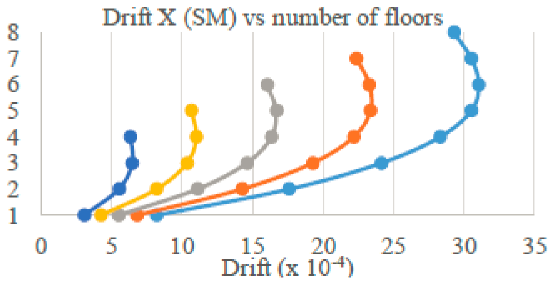

Figure 2. Drift X (SM) from 4 to 8 floors

After verifying the structure, the SSI analysis is carried out. For this, it is necessary to calculate the ballast coefficient that allows us to find an equivalence of the soil, similar to the behavior of a spring. For this evaluation of the structure, it was designed considering 3 codes: that of the American code ASCE 41-13 [7], Russian code SNIP 2-02-05-87 [8] and Mexican complementary technical code [9]. In addition, data on the soil parameters that are required by such design regulations is necessary (table 1).

Table 1. Geotechnical parameters of silty and poorly graded sand

Soil parameters	SP (Poorly Graduated Sand)	SM (Silty Sand)
Soil elasticity modulus (kg/cm^2)	190	200
Poisson's ratio	0.25	0.22
Internal friction angle (°)	26.7	27
Volumetric density (gr/cm^3)	1.681	1.52
Spread Wave Propagation Speed (m/s)	180	250

Then we proceed to calculate the 6 ballast coefficients (in the direction X, Y, Z and their respective turns). Subsequently, the support of the structure is released from the embedment to assign said coefficients, which will idealize the behavior of the land. With the help of the software, the deformation of the mezzanines and the period of the structure are calculated considering the flexibility of the floor.

As evidence is shown the results obtained from the American code ASCE 41-13 for an SP soil (table 2 to 3):

Table 2. Drift in X considering SSI according to American code ASCE 41-13 for a soil SP.

N° of floors	Drift Y - American code ASCE 41-13				
8	0.0051				
7	0.0052	0.0041			
6	0.0054	0.0042	0.0031		
5	0.0054	0.0043	0.0032	0.0023	
4	0.0053	0.0043	0.0033	0.0023	0.0015
3	0.0050	0.0041	0.0032	0.0023	0.0016
2	0.0045	0.0037	0.0029	0.0022	0.0015
1	0.0043	0.0036	0.0029	0.0023	0.0017

Table 3. Drift in X considering SSI according to American code ASCE 41-13 for a soil SP.

N° of floors	Drift X - American code ASCE 41-13				
8	0.0044				
7	0.0046	0.0035			
6	0.0047	0.0037	0.0027		
5	0.0047	0.0037	0.0028	0.0019	
4	0.0046	0.0037	0.0028	0.0020	0.0013
3	0.0043	0.0035	0.0027	0.0020	0.0013
2	0.0038	0.0031	0.0025	0.0019	0.0013
1	0.0036	0.0030	0.0025	0.0019	0.0014

Table 4. Period (seconds) of the structure considering recessing and flexibility in the base.

	Fixed-base	SSI - Russian Code		SSI – American Code		SSI – Mexican Code	
N° floors	SP o SM	SP	SM	SP	SM	SP	SM
8	0.43	0.652	0.645	0.58	0.515	0.623	0.618
7	0.348	0.551	0.545	0.486	0.427	0.526	0.522
6	0.272	0.455	0.449	0.396	0.344	0.434	0.43
5	0.203	0.363	0.358	0.312	0.266	0.348	0.344
4	0.141	0.277	0.273	0.234	0.195	0.267	0.264

As can be seen in the table 4; there is an important variation in the responses when considering the soil as an elasto-plastic element. The present investigation seeks to propose a correlation between the responses considering SSI and those of an analysis fixed in the base, with the aim of establishing a correction parameter for both the period and the mezzanine drift.

4. Results

After the analysis of the structure considering the flexibility of the soil and fixed in the base, we proceed to determine the regression that best fits the data obtained. The data that will be used for this study will have the following characteristics: the first 3 floors of the analyzed structures will not be used, since the variation of their results (SSI vs fixed), does not fit the data dispersion and the correlation will be established for structures greater than 12.00m (or 4 floors) at 35.00m (or 12 floors).

4.1. Data correlation analysis for the drifts obtained

In the first instance, correlations will be established for the variation of the drifts according to the height of the structure (Cd as a function of Ht). The variable Ht defines the building height in meters and the variable Cd defines the percentage or coefficient of drift amplification considering ISE vs fixed-base building. Consequently, the correlation is established based on the height of the building, code used and type of soil. These results can be seen in table 5, 6 and 7.

Table 5. Model and correlation factor that was designated for the Russian code SNIP 2-02-05-87 for SP and SM soil

	Russian code (SP)	Russian code (SM)
Correlation Model	Logarithm of X	Logarithm of X
Correlation	75.79%	81.62%

Table 6. Model and correlation factor that was designated for the American code ASCE 41-13 for SP and SM soil

	American code (SP)	American code (SM)
Correlation Model	Logarithm of X	Logarithm of X
Correlation	81.50%	87.13%

Table 7. Model and correlation factor that was designated for the Mexican complementary technical code for SP and SM soil

	Mexican code (SP)	Mexican code (SM)
Correlation Model	Logarithm of X	Logarithm of X
Correlation	91.71%	93.11%

These correlations were chosen because these are the ones that best fit the dispersion of data (Cd depending on the height of the building). Subsequently, the regression of data for each correlation is validated. It should be mentioned that the amount of data used for the statistical analysis is 30 values for each regression. It was obtained that the P-value (probability corresponding to the statistic if possible, under the null hypothesis) is less than 0.05; therefore, there is a statistically significant relationship with a 95.0% confidence level in all cases [10]. The functions established for the calculation of Cd as a function of Ht are the following:

$$Cd_{RC\text{-}SP}=3.9104-1.0075\ \ln(H_t) \tag{1}$$
$$Cd_{MC\text{-}SP}=3.5146-0.9071\ \ln(H_t) \tag{2}$$
$$Cd_{AC\text{-}SP}=4.6232-1.1847\ \ln(H_t) \tag{3}$$
$$Cd_{RC\text{-}SM}=4.0671-1.078\ \ln(H_t) \tag{4}$$
$$Cd_{MC\text{-}SM}=3.531-0.9226\ \ln(H_t) \tag{5}$$
$$Cd_{AC\text{-}SM}=2.6233-0.6785\ \ln(H_t) \tag{6}$$

As it was observed in the regression of the data; the mexican code has a higher correlation of data, so it would fit a better prediction of drift amplification based on their responses. However, the american code is the one that generates the greatest amplification in drifts (for the SP soil), although these results are significantly different from those obtained through the Russian and Mexican code. In figure 3 the variation of the functions defined for each code can be observed.

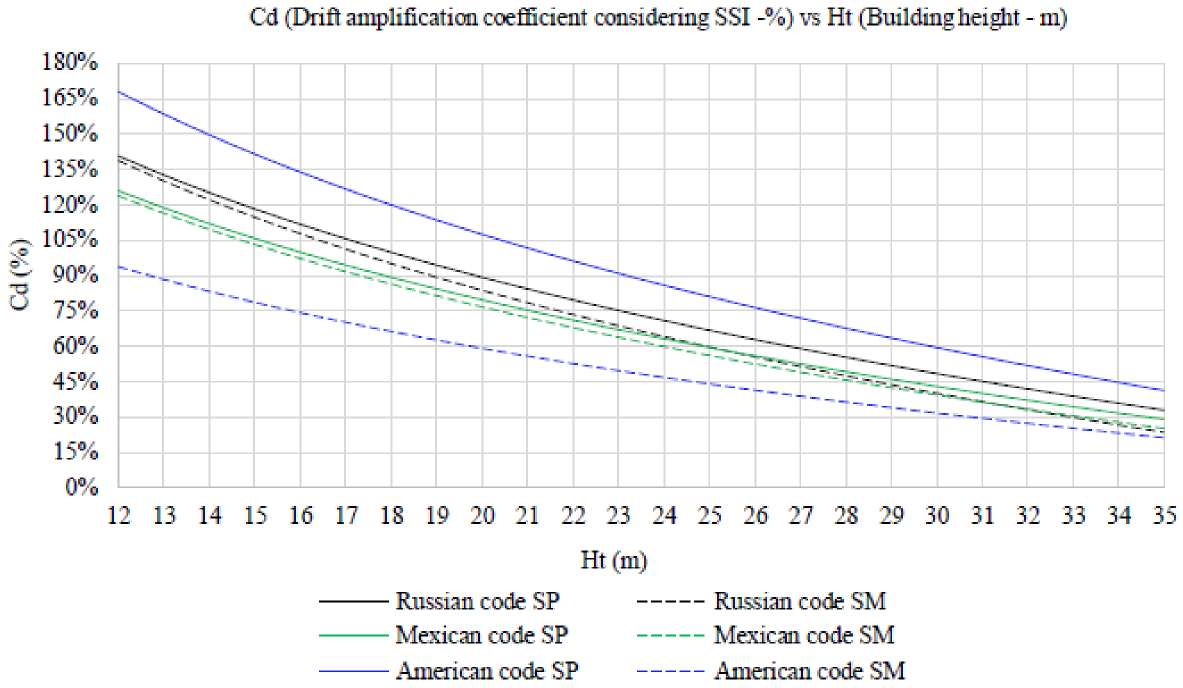

Figure 3. Cd depending on the height of the building for the Russian, Mexican and American code considering the soil SP and SM

Due to the variability of the regressions obtained from the 3 models studied, an equation is proposed that will more optimally normalize the distribution of the data to predict the value of the amplification coefficient Cd. These proposed equations have a correlation of 74.04% and 75.91% respectively, with a P-value less than 0.05 (figure 4).

$$Cd=4.0161-1.0331 \ln(H_t) \text{ to soil SP} \quad (7)$$
$$Cd=3.4071-0.893 \ln(H_t) \text{ to soil SM} \quad (8)$$

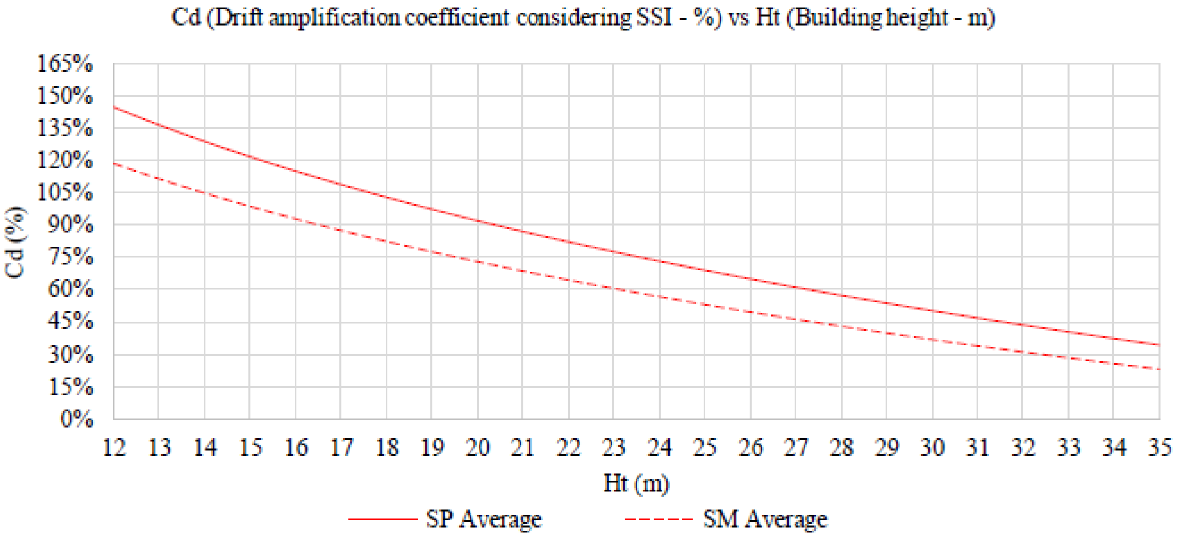

Figure 4. Cd depending on the height of the building considering the soils SP and SM

4.2. Data correlation analysis for periods

Therefore, the regression will be carried out for the periods considering the variables Ct and Ht. It should be noted that the correlation of data regarding the period of the structure exceeds 99% with a P-value of less than 0.05, so all regressions are apt to predict the behavior of the period. The variable Ht defines the building height in meters and the variable Ct defines percentage or coefficient of period amplification considering ISE vs fixed-base building (figure 5)

The functions established for the calculation of Ct based on Ht considering each code are the following:

$$Ct_{RC\text{-}SP}=(0.1412+0.0749\ Ht)^{-1} \tag{9}$$
$$Ct_{MC\text{-}SP}=(0.1714+0.0644\ Ht)^{-1} \tag{10}$$
$$Ct_{AC\text{-}SP}=\exp(2.3558-0.9938\ \ln(H_t)) \tag{11}$$
$$Ct_{RC\text{-}SM}=(0.144+0.0773\ Ht)^{-1} \tag{12}$$
$$Ct_{MC\text{-}SM}=(0.1906+0.1146\ Ht)^{-1} \tag{13}$$
$$Ct_{AC\text{-}SM}=\exp(2.3291-0.9933\ \ln(H_t)) \tag{14}$$

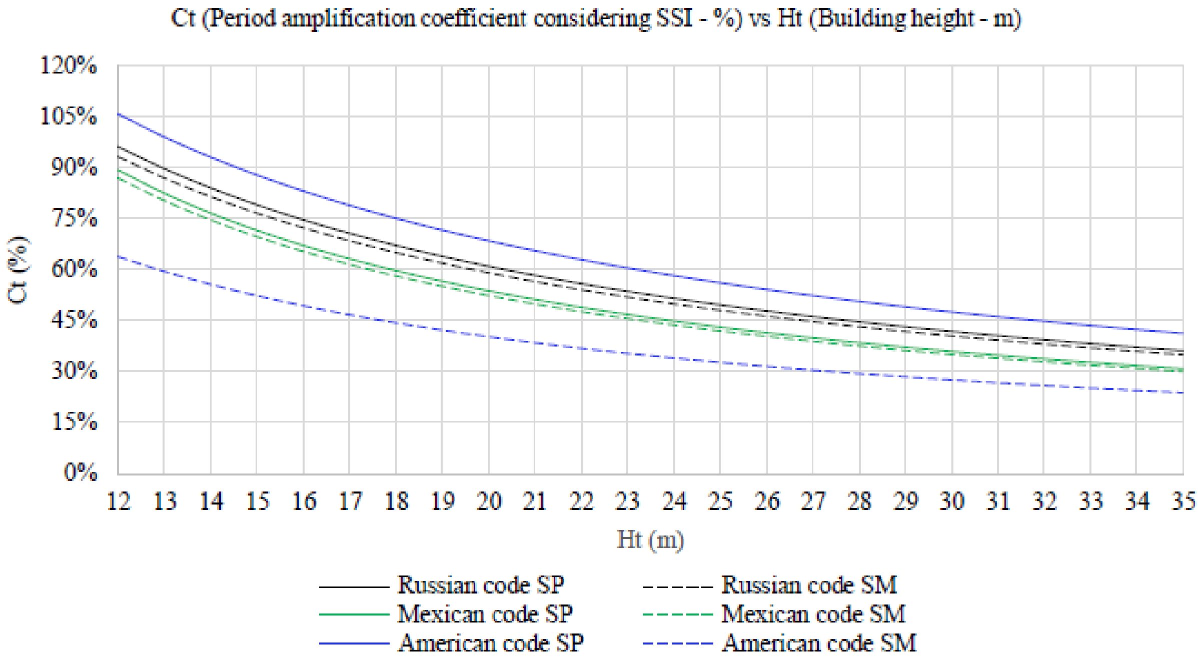

Figure 5. Ct depending on the height of the building for the Russian, Mexican and American code considering the soil SP and SM

The regression of data in terms of periods is very similar to the behavior of the drifts obtained, so a coefficient that represents the behavior of Ct is also proposed. The following equations have a correlation of 93.25% and 82.70% respectively with a P-value less than 0.05 (figure 6).

$$Ct=0.061+10.9705\ Ht^{-1} \tag{15}$$
$$Ct=0.0387+9.3288\ Ht^{-1} \tag{16}$$

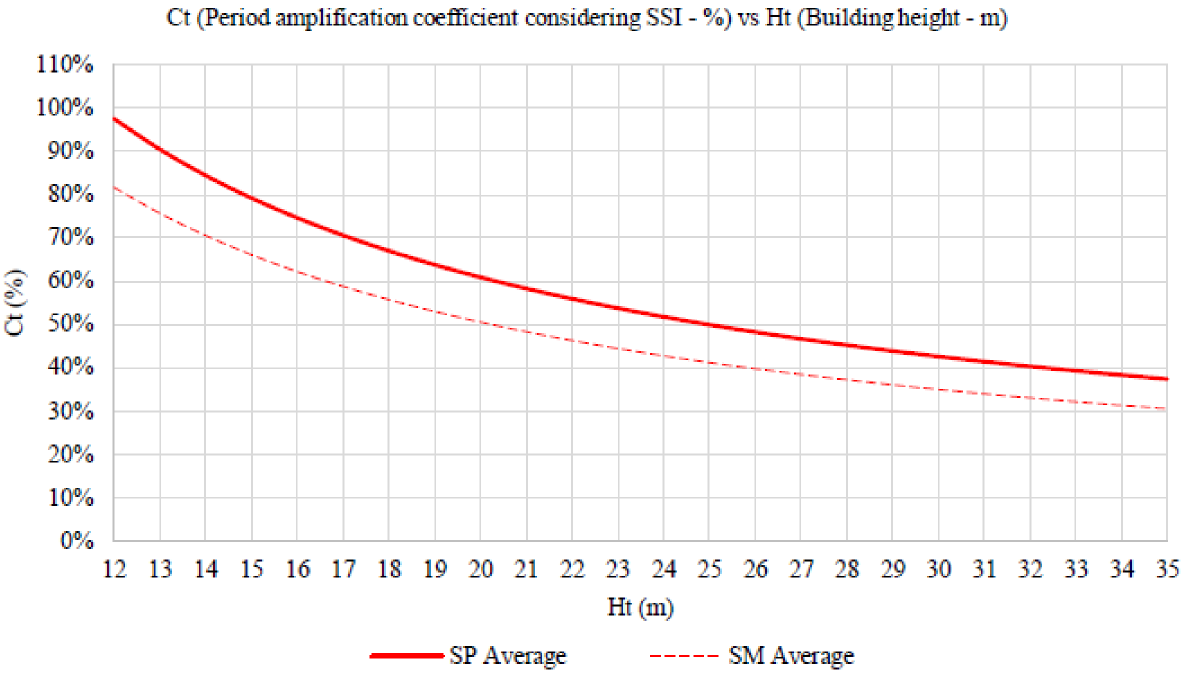

Figure 6. Ct depending on the height of the building considering the soils SP and SM

5. Conclusions

In the present work, we have proposed functions with a statistically significant relationship that allow us to know the period and the drifts of a building considering SSI from the responses of a model fixed in the base, which can be used to predict a real behavior of the structure considering the flexibility of the soil. Its application must be used for a preventive criterion of the effects that can generate failures or collapses (resonance) but not for the design due to the mentioned limitations. It can be determined that the Mexican and American code have a higher correlation of data with respect to the Russian code, the percentage of correlation being for Mexican C. 93.41%, American C. 84.32% and Russian C. 78.71% with respect to the amplification of the drifts However, it is proposed to use the functions Ct and Cd, which together predict the behavior of the three international codes analyzed. On the other hand, the method that considers values closer to the proposed functions (Ct and Cd) is the Mexican method, however, if the soil is very soft, the American code ASCE 41-13 method must also be considered to respect the maximum limit of drifts provided by any of the three code mentioned.

It is recommended to develop studies for the elaboration of a multiple regression model that considers the lateral stiffness and the height of the structure, which would modify the equations proposed in the present investigation.

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