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INFLUENCE OF THE SOIL-STRUCTURE INTERACTION (SSI) ON THE FUNDAMENTAL FREQUENCY OF STRUCTURES

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ABSTRACT

The paper concerns analysis of the influence of the soil-structure interaction on the fundamental frequency of a wide range of building structures with different geotechnical conditions. The soil-foundation system is modelled using translational and rotational discrete springs.
Numerical simulations are firstly conducted on a simple bent frame structure; this analysis leads to define a dimensionless parameter, called soil-structure relative rigidity K_{ss}. Analyses are then extended for Multi-Degree Of Freedom (MDOF) structures with multiple stories and bents. Charts are proposed for taking into account the influence of the Soil-Structure Interaction (SSI) in the determination of the fundamental frequency of a wide range of buildings.

Keywords: Building, charts, Fundamental period, relative rigidity, soil-structure interaction, seismic.

INTRODUCTION

Building codes use generally the fundamental period of buildings to assess their response to seismic loadings. This parameter is generally calculated using empirical formulas provided by seismic codes. These formulas generally ignore the influence of the soil-structure interaction, which could drastically affect the fundamental period of buildings and consequently their overall seismic response. On the base of measurements collected from buildings during earthquakes, Goel and Chopra (1998) concluded that in the case of Shear-Wall structures, empirical formulas such as those proposed by the Uniform Building Code (1997) are inadequate. Furthermore and through a series of micro-vibrations tests conducted on 20 Shear Wall building structures constructed on different soil types, Ghrib and Mamedov (2004) evaluated the fundamental period considering the flexibility at the base under low levels of vibrations amplitude. Analysis confirmed the inadequacy of the fundamental period formula given by the National Building Codes of Canada (NBCC-95) since they do not include the foundation flexibility.

In most seismic building codes, the role of the SSI is usually considered beneficial to the structural system under seismic loading since it lengthens the lateral fundamental period and leads to higher damping of the system. This conclusion could be misleading. Recent case studies and post-seismic

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observations suggest that the SSI can be detrimental and neglecting its influence could lead to unsafe design for both the superstructure and the foundation especially for structures founded on soft soil (Gazetas and Mylonakis, 1998; Mylonakis & Gazetas, 2000; Boris et al 2004).

Several authors attempted to determine the influence of the soil structure interaction (SSI) on the seismic response of buildings. First studies were conducted by Veletsos & Meek (1974; Veletsos & Nair (1975) and Bielak (1975). They established that the seismic response of a Single-Degree of Freedom (SDOF) structure with a surface foundation can be predicted by an equivalent fixed-base SDOF with modified period $\tilde{T}$ and damping $\tilde{\xi}$. The flexible-base period $\tilde{T}$ is evaluated from Velestos and Meek [5] for a structure with a surface foundation as follow:

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_u} + \frac{kh^2}{k_\theta}} \tag{1}$$

T denotes the fixed-base system period; k_u and k_θ stand for the rotational and translational springs, h and k designate the height and flexural rigidity of the structure, respectively. Similar formula is recommended by the Building Seismic Safety Council (BSSC-2003) for structures with circular mat foundation.

On the base of data recorded on 57 building covering a wide range of structural and geotechnical conditions, Stewart et al. (1999) analyzed approaches proposed by Velestos and Bielak to predict $\frac{\tilde{T}}{T}$. They found that these approaches can reliably predict the effect of inertial interaction but are limited to SDOF oscillators. The objective of the present paper concerns the elaboration of a simple procedure for taking into account the influence of the soil-structure interaction in the determination of the fundamental frequency of buildings. Analyses conducted for both one-storey and multi-storey buildings for various geotechnical conditions allow the construction of charts which give the fundamental frequency of a wide range of buildings in terms of the relative soil-structure stiffness.

ONE-STOREY BUILDINGS

Numerical model

The case study that will be firstly investigated concerns one-storey building modeled as a reinforced concrete frame founded on a homogeneous elastic soil layer. This frame is composed of a slab supported on two square columns and based on two isolated square footings (2.0 mx2.0 m). The height of each column is 4.0 m and its cross section is 0.30x0.3 m2. Dimensions of the slab floor are 5.0 x5.0 m^2 and its thickness is equal to 0.3 m. Table 1 summarizes mechanical properties of both the soil and structure materials.

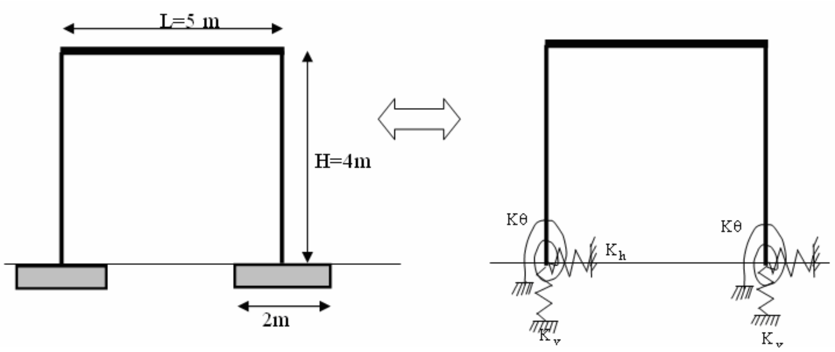

Figure 1. Numerical model for one-storey buildings

Table 1: Mechanical properties of soil-structure system – reference example

	Density γ (kN/m3)	Young Modulus E (MPa)	Poisson ratio ν	Flexural rigidity EI (kN.m²)
Soil	20	5	0.3	
Frame	24.5	32000	0.2	43200

Elastic beam elements are used to model the superstructure while the soil-foundation system is represented by means of translational (horizontal K_h and vertical K_v) and rotational (K_θ) discrete springs as illustrated in figure 1. The rigidities of these springs are evaluated from the following formulas (Newmark & Rosemblueth 1971):

- Vertical translation:

$$K_v = \frac{G_s}{(1-\nu)}\beta_z\sqrt{A} \tag{2}$$

- Horizontal translation:

$$K_h = 2(1+\nu_s)G_s\beta_x\sqrt{A} \tag{3}$$

- Rotation:

$$K_\theta = \frac{1+\nu_s}{4}G_s\beta_x(a^2+b^2)\sqrt{A} \tag{4}$$

a and b denote the dimensions of the footing; G_s and ν_s designate the soil shear modulus and the Poisson's ratio, respectively. The factors β_x and β_z account for the geometry of the foundation (b/a). For the present case study, springs rigidities are equal to K_v = 11500 kN/m; K_h= 10000 kN/m and K_θ = 10000 kN.m/rd.

Dynamic analyses were carried out using the finite element software Effel. It gives a fundamental frequency f = 2.46 Hz (T = 0.406 s). The comparison of this result with that obtained for a fixed-base model (f_{FB}=3.17 Hz) shows a difference of about 23% due to the SSI effect. This difference depends on several parameters which will be investigated in the sequel.

Soil Structure relative rigidity K_{ss}

The fundamental frequency of a fixed-base structure f_{FB} under lateral loading depends on the parameters E_c, I_c and H which stand for the Young's modulus, the moment of inertia of the vertical resisting element (column or shear wall for one storey) and the storey height. The influence of these parameters on the buildings fundamental frequency depends also on the SSI. For example, considering the reference case, the ratio f/f_{FB} decreases from 0.76 to 0.415 (decrease of 86 %) when the inertia moment of the vertical elements increases from I_c= 0.00135 to Ic = 0.0135. This difference is less significant for a stiffer soil with a Young's modulus E_s = 30 MPa where f/f_{FB} decreases from 0.951 to 0.726 (decrease of 30 %) for the same variation in I_c.

On the other hand and as indicated before, the influence of the SSI is taken into account through the rotational and translational springs (Eq. 2-4) which are function of the soil modulus E_s and the foundation area A.

As a consequence, the fundamental frequency f could be expressed as:

$$f = F\,(E_s, H, E_c, I_c, A) \tag{5}$$

This equation shows that the fundamental frequency of the soil-foundation- structure system depends on five parameters which characterize the soil (E_s), the foundation (A) and the structure (H, I_c, E_c). Analyses were conducted for different values of these parameters (Table 2) in order to identity a dimensionless factor representing the soil-structure relative rigidity. Results of these analyses are summarized in the appendix. They were approximated using the following multilinear regression:

$$Log(f / f_{FB}) = A_1 Log(E_s) + A_2 Log(H) + A_3 Log(E_c) + A_4 Log(I_c) \qquad (6)$$

f_{FB} designates the fundamental frequency of the fixed-base structure (without SSI effect). Values of the coefficients of the multilinear regression $A_1 \rightarrow A_4$: A_1=0.17; A_2=0.39; A_3=-0.19 and A_4=-0.12. They were obtained with a determination coefficient R2 = 0.75.

The regression analysis shows that the influence of soil Young's Modulus E_s is equivalent to that of the structure E_c. Normalizing the coefficients of the regression by A_1 gives $A_2/A_1 \approx 3$; $A_3/A_1 \approx 1$; $A_4/A_1 \approx 0.75$. As a consequence, the proposed dimensionless parameter K_{ss} representing the soil-structure relative rigidity could be expressed as follows:

$$K_{ss} = \frac{E_s \times H^3}{E_c \times (I_c)^{3/4}} \qquad (7)$$

To incorporate the influence of the foundation area, the expression of the soil-structure relative rigidity K_{ss} is turned into:

$$K_{ss} = \frac{E_s \times H^3 \times \sqrt{\frac{A}{A_0}}}{E_c \times (I_c)^{3/4}} \qquad (8)$$

A_0 denotes a reference area (1 m^2).

Table 2: Parameters used in the parametric study

Parameter	Values
Soil Young's modulus Es (MPa)	5 (soft soil), 10, 20, 30, 60, 100 and 200 (stiff soil)
Storey height H (m)	2, 4, 7, 10 and 13
Inertia Moment of Vertical elements Ic (m4)	0.000139, 0.00135, 0.0131, 0.1357
Young's modulus of the superstructure Ec (MPa)	20000, 32000 and 42000

Figure 2 shows the variation of the ratio f/f_{FB} with the relative rigidity K_{ss}. It can be observed that this variation can be approximated using a simple chart. For $Log(K_{ss}) > 1.5$, the ratio f/f_{FB} attains an asymptote $f/f_{FB}= 1$. In this case, the fundamental frequency of the soil-foundation-structure system is close to that of a fixed-base structure. For $Log(K_{ss}) < 1.5$, an important variation is observed for f/f_{FB} with $Log(K_{ss})$. In this case, neglecting the SSI could lead to a significant missestimation of the fundamental frequency the soil-foundation-structure system and consequently to a poor prediction of the overall dynamic response of the structure. For stiff structures on soft soils ($Log(K_{ss}) < -1$), the frequency of the fixed-base model f_{FB} exceeds by 4 times the frequency of the soil-foundation-structure system.

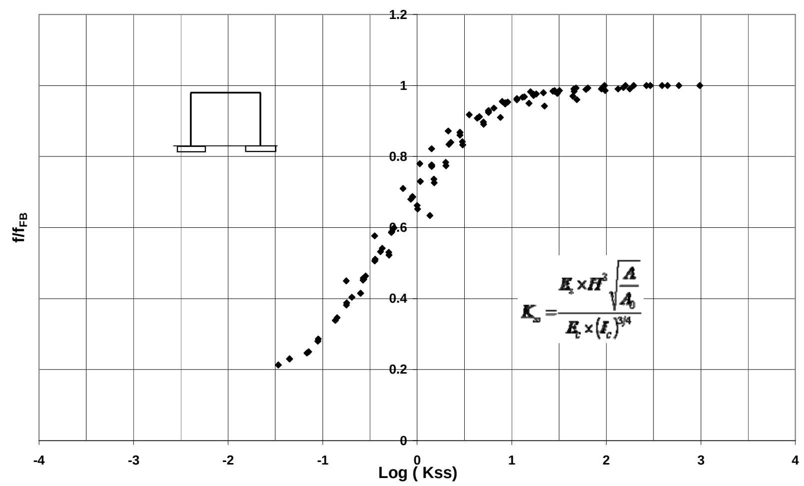

Figure 2: Influence of K_{ss} on the fundamental frequency of one-storey building

MULTI-STOREY BUILDINGS

Investigations were conducted for multi-storey buildings with different conditions for both the soil and the structure. Results obtained for buildings with different values of the total number of stories N_s (1, 3, 5, 7 and 10) and one span in both the longitudinal and transversal directions show that the soil-structure relative rigidity can be expressed as follows:

$$K_{ss} = \frac{E_s \times H^3 \times \sqrt{\dfrac{A}{A_0}}}{\mathbf{N_s} \times E_c \times \left(I_c\right)^{3/4}} \tag{9}$$

This expression indicates a decrease of K_{ss} with the increase in the number of stories, and consequently to an increase in the influence of the SSI on the fundamental frequency of the building. Figure 3 depicts the variation of f/f_{FB} with the relative rigidity K_{ss}. This variation can be approximated using a simple chart which is similar to that obtained for one-storey buildings.

Calculations were also conducted for multistorey buildings with different values of the number of spans in both the transversal and longitudinal directions (N_{bt} and N_{bl}). Analyses show that the relative rigidity for these buildings can be expressed as follows:

$$K_{ss} = \frac{\mathbf{N_{bt}} \times \mathbf{N_{bl}} \times E_s \times H^3 \times \sqrt{\dfrac{A}{A_0}}}{N_s \times E_c \times \left(I_c\right)^{3/4}} \tag{10}$$

The increase in the number of spans (N_{bl} or N_{bt}) leads to higher values of the relative rigidity K_{ss} and consequently to a decrease in the influence of the soil-structure interaction. Figure 4 depicts the variation of the fundamental frequency ratio (f/f_{FB}) with K_{ss} for buildings with multiple stories and spans. It can be observed that this variation is similar to that obtained for one-storey buildings.

Figure 5 summarizes results obtained for one storey and multi-storey buildings. It can be observed that the fundamental frequency ratio (f/f_{FB}) can be determined in terms of the relative rigidity K_{ss} (Eq. 10) using the chart described earlier for one-storey buildings.

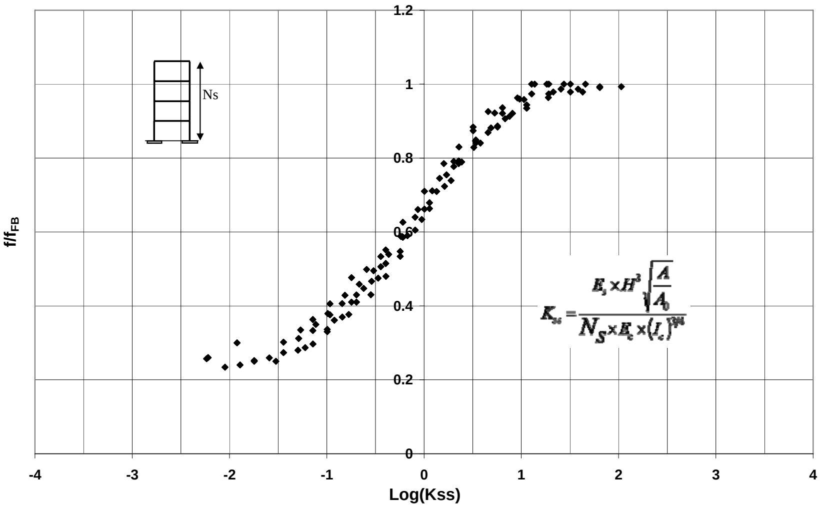

Figure 3. Influence of K_{ss} on the fundamental frequency of multistorey buildings with one span in the lateral and transverse directions

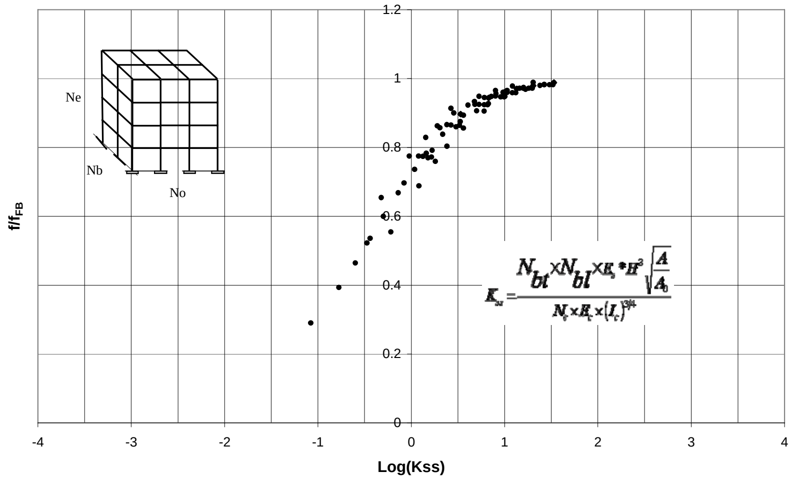

Figure 4. **Influence of K_{ss} on the fundamental frequency of 3D buildings structures**

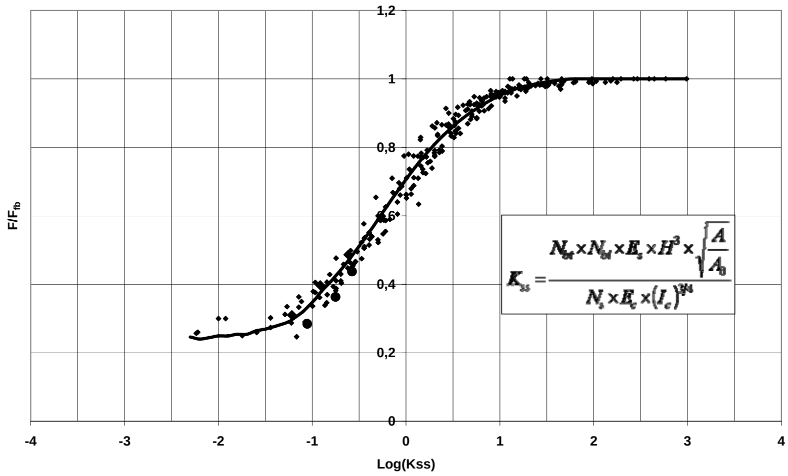

Figure 5. Chart for the consideration of the SSI in the determination of the fundamental frequency of buildings

CONCLUSION

This paper included analysis of the influence of the soil-structure interaction on the fundamental period of buildings. Analyses conducted for various soil and structure conditions showed that this influence depends mainly on the soil-structure relative rigidity, which can be expressed in terms of the soil young's modulus (E_s), the foundation area (A), the flexural rigidity of the building columns (I_c, E_c), the storey height (H) and the number of stories (N_s) and spans (N_{bt}, N_{bl}) as follows:

$$K_{ss} = \frac{N_{bt} \times N_{bl} \times E_s \times H^3 \times \sqrt{\frac{A}{A_0}}}{N_s \times E_c \times \left(I_c\right)^{3/4}} \tag{11}$$

A chart is proposed for an ease consideration of the influence of the soil-structure interaction in the determination of the fundamental frequency of buildings. For flexible buildings (Log (K_{ss})>1.5), the soil-structure interaction could be neglected. For lower values of K_{ss}, neglecting the SSI could lead to a significant missestimation of the fundamental frequency of buildings.

Note that the discrete springs used in the present study don't take into account the non linearity in the soil neither a possible uplift of the foundation. Work is currently in progress to incorporate these effects using a three-dimensional modeling of both of the soil and the structure.

APPENDIX A

Influence of K_{ss} on the fundamental frequency of one-storey buildings (Input parameters are summarized in table 2)

f / fFB	**E_s (MPa)**	**H (m)**	**E_c (MPa)**	**I_c (m^4)**
0.955	5	4	32000	0.000139
0.982	10	4	32000	0.000139
0.986	20	4	32000	0.000139
0.993	30	4	32000	0.000139
0.993	40	4	32000	0.000139
1.000	60	4	32000	0.000139
1.000	100	4	32000	0.000139
0.776	5	4	32000	0.00135
0.868	10	4	32000	0.00135
0.929	20	4	32000	0.00135
0.951	30	4	32000	0.00135
0.963	40	4	32000	0.00135
0.976	60	4	32000	0.00135
0.985	100	4	32000	0.00135
0.415	5	4	32000	0.01315
0.522	10	4	32000	0.01315
0.652	20	4	32000	0.01315
0.726	30	4	32000	0.01315
0.774	40	4	32000	0.01315
0.833	60	4	32000	0.01315
0.891	100	4	32000	0.01315
0.230	5	4	32000	0.135757
0.287	10	4	32000	0.135757
0.388	20	4	32000	0.135757
0.457	30	4	32000	0.135757

f / f_{FB}	**E_s (MPa)**	**H (m)**	**E_c (MPa)**	**I_c (m^4)**
0.989	40	7	32000	0.00135
0.994	60	7	32000	0.00135
0.994	100	7	32000	0.00135
0.942	5	10	32000	0.00135
0.970	10	10	32000	0.00135
0.990	20	10	32000	0.00135
0.990	30	10	32000	0.00135
0.990	40	10	32000	0.00135
1.000	60	10	32000	0.00135
1.000	100	10	32000	0.00135
0.960	5	13	32000	0.00135
0.986	10	13	32000	0.00135
1.000	20	13	32000	0.00135
1.000	30	13	32000	0.00135
1.000	40	13	32000	0.00135
1.000	60	13	32000	0.00135
1.000	100	13	32000	0.00135
0.840	5	4	20000	0.00135
0.912	10	4	20000	0.00135
0.953	20	4	20000	0.00135
0.968	30	4	20000	0.00135
0.976	40	4	20000	0.00135
0.984	60	4	20000	0.00135
0.990	100	4	20000	0.00135
0.250	5	4	20000	0.135752

0.511	40	4	32000	0.135757
0.589	60	4	32000	0.135757
0.686	100	4	32000	0.135757
0.450	5	2	32000	0.00135
0.577	10	2	32000	0.00135
0.710	20	2	32000	0.00135
0.780	30	2	32000	0.00135
0.822	40	2	32000	0.00135
0.872	60	2	32000	0.00135
0.917	100	2	32000	0.00135
0.776	5	4	32000	0.00135
0.868	10	4	32000	0.00135
0.929	20	4	32000	0.00135
0.951	30	4	32000	0.00135
0.963	40	4	32000	0.00135
0.976	60	4	32000	0.00135
0.985	100	4	32000	0.00135
0.910	5	7	32000	0.00135
0.950	10	7	32000	0.00135
0.978	20	7	32000	0.00135
0.983	30	7	32000	0.00135

0.346	10	4	20000	0.135752
0.464	20	4	20000	0.135752
0.542	30	4	20000	0.135752
0.599	40	4	20000	0.135752
0.680	60	4	20000	0.135752
0.772	100	4	20000	0.135752
0.730	5	4	42000	0.00135
0.834	10	4	42000	0.00135
0.908	20	4	42000	0.00135
0.936	30	4	42000	0.00135
0.951	40	4	42000	0.00135
0.967	60	4	42000	0.00135
0.980	100	4	42000	0.00135
0.200	5	4	42000	0.135753
0.247	10	4	42000	0.135753
0.339	20	4	42000	0.135753
0.404	30	4	42000	0.135753
0.455	40	4	42000	0.135753
0.532	60	4	42000	0.135753
0.634	100	4	42000	0.135753

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