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INFLUENCE OF THE SOIL-STRUCTURE INTERACTION ON THE SEISMIC BEHAVIOR OF BUILDINGS ON SHALLOW FOUNDATIONS

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ABSTRACT: The objective of this work is to study the mobility of shallow foundations relative to the subgrade by considering two cases. In the first, the structure is fixed at its base. For the second, the foundation is replaced by hinges and springs, where their stiffnesses are expressed in terms of the geometry of the foundation and soil shear strength. The comparison is made on a dynamic model when the two tested cases are confronted. Thereafter, a parametric study is considered to see the effect of all the parameters that can play a key role in the structural response. Then, these results will be validated on real structure cases, by considering important Algerian earthquakes: the one of Aïn Témouchent in 1999 and the earthquake of Boumerdès in 2003. The extracted results will permit to make the point on all the elements that may influence the seismic response of buildings while considering the interface soil-foundation-structure.

Keywords: Dynamic Analysis, Shallow Foundations, Soil Structure Interaction, Shear Velocity.

INTRODUCTION

The design of a structure in a seismic zone is highly dependent on the knowledge of seating elements, namely soil and foundations. These latter are the interface between the soil with which they move, and the superstructure that undergoes inertial forces. In addition to the vertical loads that they ordinarily transmit, the horizontal earthquake action is added. The soil itself is susceptible to deform or even lose its cohesion. Geotechnicians describe the expected behavior of soils, when shaken by deformations, settlements or landslides, or an amplification of waves of certain frequencies. Engineers, in their turn, take this into account for the project in general and the foundations in particular. For the public authority, it takes this into account for planning regulations that prohibit the construction in certain sites or require special foundations.

However, most structural studies do not take into account the foundations mobility relative to the subgrade. Indeed, the building design considers the superstructure fixed on the ground. However, this assumption is not always justified, given that the behavior of a building that is supposed to be fixed in the ground is not the same when the fixed joint is replaced by hinges with springs that schematize the freedom of movement of foundations. In some seismic regulations, such as the Algerian earthquake regulation (RPA 99 V2003, [6]) this matter is not addressed.

In the present work, analyses of the influence of Soil-Structure Interaction (SSI) on the fundamental frequency of building structures are proposed. A model of a simple frame, composed of two columns and a beam representing the floor, is considered (Fig. 1). The SSI phenomenon is carried by modeling the whole soil-foundation with 6 springs: 3 translations and 3 rotations. This model has been proposed by many authors, as Parmelee in 1967, Veletsos et al. in 1974, 1975, 1977, Jennings et Bielak in 1973, Wolf in 1985 and Aviles et al [4]. in 1996, 1998. The results of this analysis will be compared to those found in another model in which the base is considered as fixed.

SYSTEM MODEL AND FORMULATION

The fundamental frequency of building type structures constitutes an essential parameter in the design and the structural analysis in the seismic zone. This parameter is usually calculated by using empirical formulas provided by the seismic regulations that generally neglect the SSI. However, this interaction can have a significant influence on the fundamental frequency, and thus, can lead to wrong structural design. Indeed, some authors (Gazetas and Mylonakis 1998, 2000, [2], [3]) showed that the post-seismic observations revealed that the SSI can have a detrimental effect on the structures. Additionally, numerical simulations, carried out by Boris et al. (2004) [1], showed that the SSI can have advantageous or harmful effects on the structural behavior, according to the characteristics of soil and those of the seismic loading [4].

The springs' stiffnesses (translation and rotation) are determined using formulas that are available in literature. The formulas of (Newmark and Rosemblueth 1971, [5]) express the stiffness in terms of the soil mechanical characteristics, namely the shear modulus G_s and Poisson's ratio ν. Also, in terms of the geometrical characteristics of the foundation:

$$K_v = \frac{G_s}{(1+\nu)}\beta_z\sqrt{A} \quad (1)$$

$$K_h = 2(1+\nu)G_s\beta_x\sqrt{A} \quad (2)$$

$$K_\theta = \frac{1+\nu}{4}G_s\beta_x(a^2+b)\sqrt{A} \quad (3)$$

K_v, K_h et K_θ represent respectively the vertical, the horizontal and the rotational translational stiffnensses, and A is the foundation area, $A= a*b$.

The parameters β_x and β_z are two entities depending on the *a/b* ratio. For the case of a square foundation of 2*2 m^2, β_x= 1 et β_z= 2.18 [7].

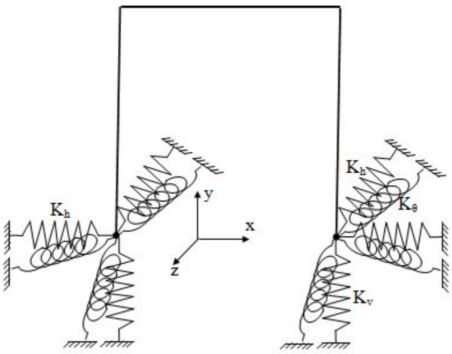

Fig. 1 Reference model

The mechanical characteristics of the used materials are given in the table 1

Table 1 Mechanical characteristics of the studied system

	Density γ (KN/m^3)	Elastic modulus E (MPa)	Poisson's ratio
Soil	20	52	0.3
structure	24.5	32000	0.2

The modal analysis of the selected frame was carried out. The different fundamental modes of the two cases (fixed and by considering the SSI) were extracted. In the first case, the fundamental frequency is found equal to 8.13Hz, where in the second; it is equal to 5.53Hz. Therefore, a reduction of 32% in the fundamental frequency when considering the SSI is seen. The found fundamental mode represents a translation in X direction whatever the treated case is.

PARAMETRIC STUDY

Modal dynamic analyses of the studied frame were carried out for different structural configurations by varying the parameters affecting the fundamental frequency, particularly, the basic parameters relative to the soil and the structure.

The objective is to determine the relationship between the modal fundamental frequency of the fixed model (F_{fix}) and the one of the same model when the SSI is considered (F_{SSI}). The obtained results will permit to bring out the influence of SSI on the fundamental frequency of the buildings.

It should be noted that this can be expressed according to (V_s, E_p, I_P, N_b, N_o, H, L, A). Where V_s is the soil's shear velocities waves, E_p and I_P are respectively, the Young modulus and the moment of inertia of the columns, H is the height of floor, L is the span, and A is the foundation area. N_e is the number of floors, N_b and N_o are the building's openings number in the longitudinal and the transversal directions, respectively.

Initially, the analysis is carried out for a simple frame comprising one floor and one opening.In this case, the fundamental frequency of the frame is expressed only according to V_s, E_p, I_P, H, L, and A.The considered values in this parametric study are summarized in table 2. The soil's shear velocities are taken from the RPA 99 (V2003) [6] regulation for different types of soils: very friable, friable, firm, very firm and rock.

Table 2 Considered parameters values

V_S (m/s)	100 (Very friable) 150 (Very friable) 200 (Friable) 400 (Firm) 800 (Rock)
E_P (MPa)	20000 32000 42000
I_P (m^4)	0.000325 0.00125 0.00342 0.00762 0.0149 0.0341
H (m)	2.00 4.00 6.00 8.00 10.00
A_{column} (cm²)	25x25 35x35 45x45 55x55 65x65 80x80

Results

Figs.2 to 5 show the parametric study results for different configurations. The different elements are represented according to the F_{SSI}/F_{fix} frequency ratio.

In the case of the V_s influence, this ratio is stabilized for velocities greater than 400m/s. For less resistant soil, the effect of the SSI remains very visible.

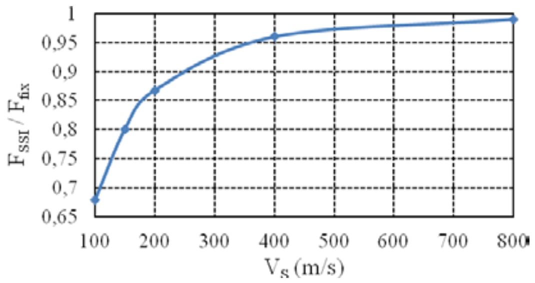

Fig.2 Influence of V_s on the frequencies ratio

The inertia variation of columns influences considerably on the F_{SSI}/F_{fix} ratio (Fig. 3). Indeed, for velocities V_s lower than 400m/s, the reduction of the frequency F_{SSI} can reach the 70%, compared to the case of the fixed structure. It is shown also that more the inertia of columns increases, more it becomes judiciable to considerer the SSI effect.

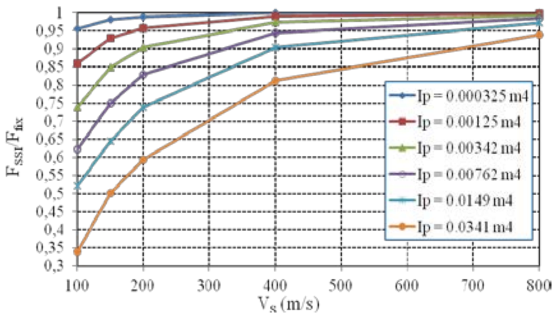

Fig.3 Influence of I_p on the frequencies ratio

The fundamental frequency is affected also by the building's height variation as shown in fig. 4. In the cases where the height H is lower than 8.00m, the variation between the two frequencies F_{SSI} and F_{fix}, and for the same velocities, are not significant. However, the difference becomes clear when $H\geq 8.00$m.The rigidity of columns does not have a great influence, since the variation of F_{SSI}/F_{fix} has practically the same curve shape for different Young modulus (Fig. 5).

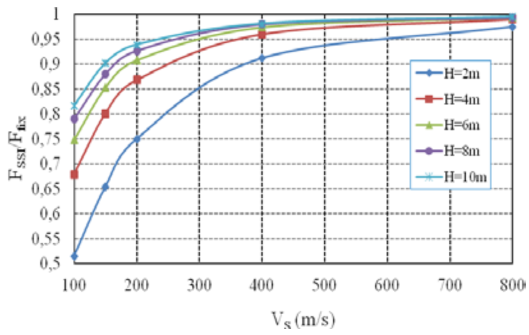

Fig.4 Influence of H on the frequencies ratio

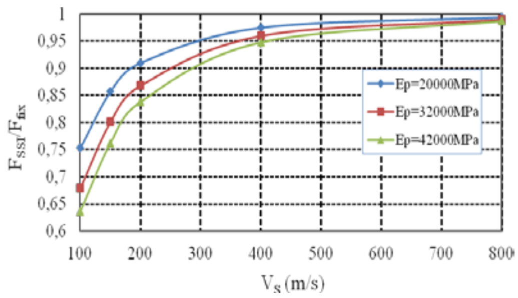

Fig.5 Influence of E_p

Finally, one can note that for some configurations (stiff structures on soft soil), the F_{SSI}/F_{fix} ratio can reach low values, close to 0.3, thing that means that the SSI lead to a reduction of about 70% of the fundamental frequency of the frame. This confirms the need to consider the SSI for the determination of the fundamental frequency for this type of structures.

SSI CONSIDERATION METHOD

A non-dimensional parameter was proposed by Khalil [4], noted K_{SS}, in order to express relative stiffness of soil-structure. This one can be determined according to the parameters used in the previous paragraph: V_s, H, E_p and I_P, determined by Eq. 4.

$$K_{SS} = \frac{N_o \cdot N_b \cdot \rho \cdot V_s^{\,2} \cdot H^3 \cdot \sqrt{\dfrac{A}{A_0}}}{N_e \cdot E_p \cdot I_p^{\,0,75}} \tag{4}$$

Where A_0 is a referential area (equal to1m²), ρ is the soil density and A is the foundation area.

Different configuration cases made possible to trace the abacus of the fig. 6. The found results indicate that for a calculated K_{SS} according to a building data, a corresponding F_{SSI}/F_{fix} ratio will be got.

In order to check the proposed abacus, two cases of constructions implemented in the region of Tlemcen, west of Algeria, are studied. This zone is classified as low seismicity zone (Zone I).

The first is a five story building, with 4 openings in the longitudinal direction and 3 in the transverse one. The second example is a seven story building, with 5 openings in the longitudinal direction and 3 in the transverse one. The case of a five story construction was selected to be based on isolated footings, and the other one (building with seven floors), built on continuous footings. The parameter K_{SS} was calculated according to the data of the two buildings and the result permit to plot the curves of the fig. 6.

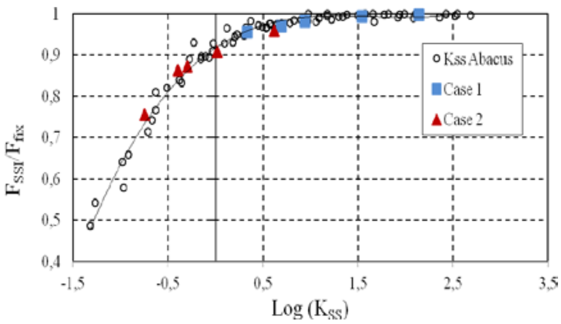

Fig. 6 Relative stiffness influence K_{SS} on the structure frequency in the two buildings

According to the obtained results, we note that the suggested parameter K_{SS} represents well the two buildings cases based on the two types of shallow foundations.

SEISMIC STUDY

In this part, the influence of the SSI on the dynamic response of the structure will be seen. For this effect, the building already studied in the previous paragraph (Case 2) is selected . In that structure, shear walls are added to its frame system. These walls are modelled as SHELL elements type. The numerical model is presented in fig. 7.

Two important Algerian earthquake cases were concidered. The first, touched the region of Aïn Témouchent in 1999 (west of Algeria) and the second (Boumerdès) has caused enormous human and material damages in 2003 (north-east region of the country). This earthquake of 6.8 of magnitude was felt for a long distance from the epicentre (Majorque to approximately 300km). The Boumerdès earthquake occurred in a zone where the seismic activity was regarded as moderate.

The zone of Tlemcen, being described as low seismicity compared to the one of Boumerdès, enabled us to consider only one the third (1/3) of the accelerogram recorded at the Keddara station. Figures 8 and 9 represent the accelerograms of the two studied cases.

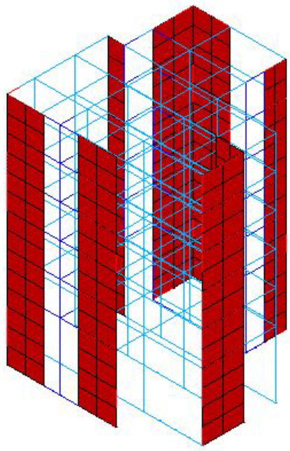

Fig.7 Numerical built model

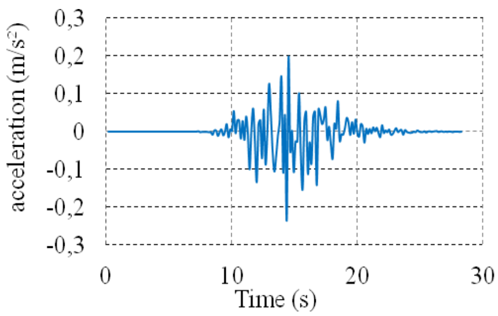

Fig.8 Aïn Témouchent Accelerogram

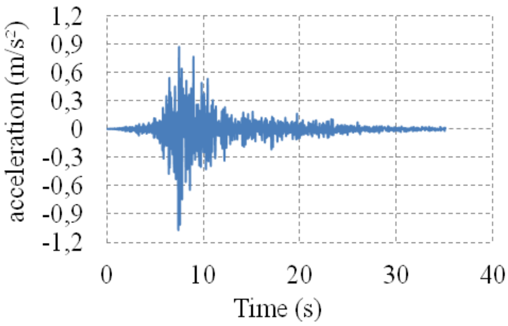

Fig.9 Boumerdès Accelerogram

As results, we presented the obtained accelerations by considering the structure as fixed and considering the spring elements modeling the mobility of the foundations relative to soil, and the displacements of the node at the highest point of construction.

For Aïn Témouchent earthquake, the acceleration graph is composed of two sections (Fig. 10). The first varies from 0 to 10 seconds, where the values are not comparable. They are very significant from the first moments of the excitation, whereas in the case of the fixed structure, those are minimal. After that, the second interval comes where the values are similar with small differences.

Horizontal displacements are represented in fig. 11. The maximum displacement is seen in the first section (from 0 to 10s), it is equal to 6.74cm in the case of the SSI, whereas in the fixed structure case, this phase illustrates a minimal displacement. Its maximum comes only to after 12.54 seconds from the beginning of the excitation; its value is around 1.66cm.Also, at the end of the excitation, the case of the SSI needs more time to be damped, since the displacement is not vanished, contrary to the fixed structure case.

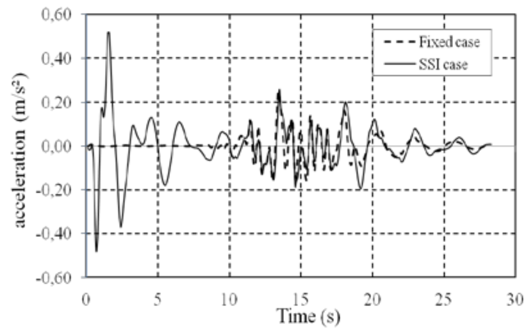

Fig.10 The SSI effect on the acceleration, Aïn Témouchent earthquake

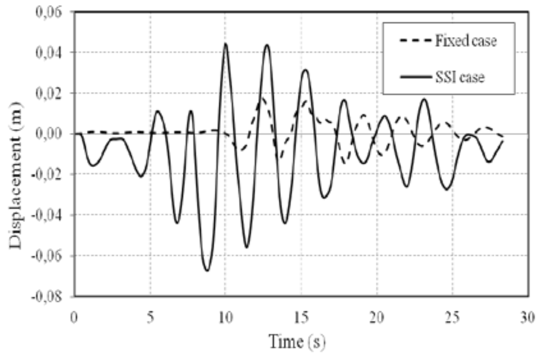

Fig.11 The SSI effect on the horizontal displacement, Aïn Témouchent earthquake.

For the earthquake of Boumerdès, the first noted remark concerns the maximum acceleration that exceeds the 0.33g in the case of the SSI. Indeed, this value exceeds the 0.5g, and it is reached before the one obtained in the fixed case with a gap of around 0.6 seconds (Fig. 12). Furthermore, at the beginning of the excitation, the acceleration is much more significant in the case of the SSI compared to case of fixed structure.

For the displacements (Fig. 13), it is noted that the values are much more significant in the case of the SSI than in the fixed case. The maximum displacement passes from 2.5cm in the fixed structure case to more than 7.5cm in the SSI case; that is 5cm of difference.

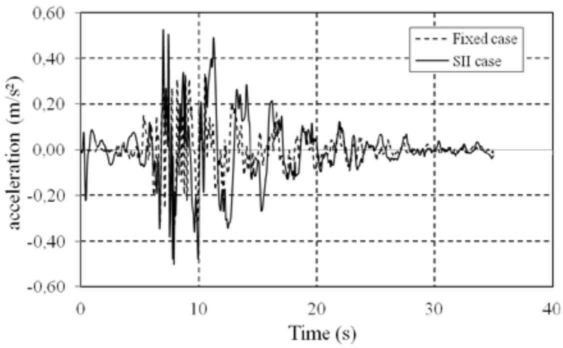

Fig.12 The SSI effect on the acceleration, Boumerdès earthquake.

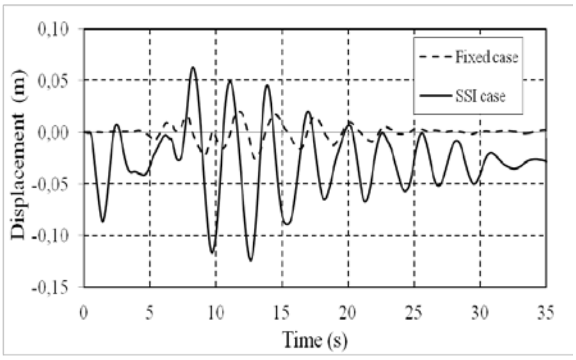

Fig.13 The SSI effect on the horizontal displacement, Boumerdès earthquake.

CONCLUSION

This paper comprised the study of the influence of the soil-structure interaction on building type structures with shallow foundations, using a numerical modeling, and based on the finite element method.

The structure was modeled by beam elements, where the soil-foundation unit was modeled using 6 springs: 3 in translation and 3 in rotation. Their stiffnesses were determined from suggested expressions, available in the literature.

The study on the influence of the soil-structure interaction on the fundamental frequency of the structures showed that this one can reduce very significantly the first frequency of the structures.

The parametric analysis permit the determination of the expression of a non-dimensional parameter, called relative stiffness of soil-structure (K_{SS}), allowing to take into account the influence of the SSI in the calculation of the fundamental frequency of the buildings and this was shown by the treatment of two cases of real buildings.

The study of the seismic response of the buildings was carried out by using two real seismic recordings. It was shown that the fact of considering the effect of the soil-structure interaction increases considerably the acceleration as well as the displacements of last floor of the building. These values seem critical especially at the beginning of the excitation.

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